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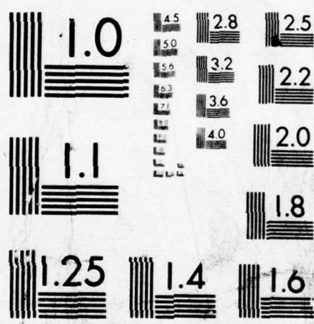

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ABSTRACT

The development of a method for uniquely characterizing the many different symbols which are used to represent data and having this characterization general enough to allow for minor variations in the symbols would enable a computer to obtain information directly from written text.

The characterization consisted of obtaining a Fourier Transform representation for each character of the alphabet and a study of the harmonic spectral density in order to obtain a pattern by which the character may be recognized. The pattern by necessity must be unique and recognizable. After establishment of the reference alphabet, each character was distorted in a like manner so that the effects of the distortion upon all the harmonic coefficients could be seen. The letters, A, E, R, and S were studied in greater depth and the results are given.

The characterizations obtained from these methods show a definite uniqueness of representation and accordingly a reference alphabet was characterized. The resolution used in obtaining the Fourier Transform representation seemed to be the major limiting factor as to the amount of distortion acceptable. The most important outgrowth of the thesis was the fact that, by using only the resolution which was used in the characterization of the listed

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reference set, a machine should be capable of reading almost any material consisting of capital letters and being somewhat symetric in physical shape.

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Throughout my undergraduate and graduate programs, the instructors have not only taught me the knowledge basic to all electrical engineers but more importantly they have taught me how to think through a problem while making use of the knowledge I have. For this very important asset, I wish to sincerely thank all of the engineering instructors. In particular I would like to give special thanks to Dr. B. F. Brown for his generous help and assistance during the preparation of this thesis.

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Chapter 1

INTRODUCTION

Objectives

The ability to rapidly perform repetitive calculations and store large amounts of data are only two of the many advantages of a computer. Before either of these abilities can be used, the machine must first receive its commands and data from a set of rigidly standardized symbols which man uses as his communications link with the machine. These symbols must follow strictly uniform patterns as to height, width, and relative positioning one to the other. Because of the need for this rigid standardization, man must do the translating of his knowledge, which is usually in the form of printed text, into symbols recognizable by the machine. Although man may use the same set of symbols as that of a machine, he restricts his symbols to very little uniformity. This is shown best by noting that the English language has but one alphabet consisting of twenty six letters (symbols), yet there are almost unlimited variations of each letter used. However, in most cases no matter what variations are used, man is able to distinguish one letter from another. If a computer was likewise able to distinguish one nonuniform character of the alphabet from another, then such a machine could obtain information directly from text written in almost any form or format.

In the machine's case, as in the human case, there are limitations in the amount that a symbol can be varied and still be

recognizable. The limitations are almost totally dependent upon how intelligent the machine is or put another way, how much information about a specific character the machine has access too. Since a rigidly standardized alphabet requires the minimum amount of information necessary to distinguish one character from another, this is the place to begin the characterization.

Method of Procedure

As mentioned before, one of the computer's greatest advantages was its ability to rapidly perform repetitive calculations. Thus, if a mathematical model were used to represent each character of the alphabet, then the machine could be used to obtain this representation. The specific math model used was important only to the point that it be understandable, its computations be relatively short, and it must uniquely represent each letter or symbol. The uniqueness of representation was the most important aspect of the mathematical model.

After a suitable method of modeling was established for a particular reference alphabet, the characterization of each symbol was tested to see how much distortion was permissible while still having the representation recognizable. Because of the many different ways a character may be distorted, an extremely comprehensive study would have to be made if one wishes the representations to extend any further than the printed alphabet. This paper, however, limited itself to the considerations of only the Futura (5) type capital letters. This set of characters was used as the reference set referred to in this paper because of their geometric structure and uniformity of stroke. The type also seemed to give the best

accessible example of a commonly acceptable alphabet which was readable and easily reproduced by hand or machine.

Although the entire reference alphabet is distorted in only a few ways, four specific characters are chosen and studied in greater depth. The results of the studies are given in the appropriate section. They are not conclusive, but they do show certain interesting aspects about the mathematical modeling and characterization schemes used. For example, the characteristic patterns obtained by the limited resolution are unique, easily recognizable, and seemingly can withstand any normal distortion which occurs.

Chapter 2

THEORY

An Overview

If the capabilities of a computer are to include the optical scanning, understanding, and manipulation of text written in a nonuniform alphabet, the machine must be able to distinguish one character from another. The scanning and manipulation of information has already been developed to a high state, but the understanding of information is still dependent upon the machine's capacity for character recognition. Since the computer is just an extension of man's own abilities, it would seem possible to extend to a machine the process used by man in character recognition. The identification and implementation of such a process must begin at a very basic level, and from here it can be built upon.

The basic level referred to is that point which is equivalent to a child's learning the alphabet. This first set of characters must be distinct, recognizable, and easily reproduced because from this point on the child will mentally refer to this base set whenever there is need of character recognition. So, as with the child, the computer must have a reference set of characters for future referral needs.

Since the ultimate goal is recognition of nonuniform characters, the computer must store this reference set in such a form that limited distortion of individual characters will not matter. Man overcomes the problem of recognizing distorted characters by observing the shape

of a particular character and comparing this shape to his reference set. Admittedly, this is an oversimplification of man's mental process, but for the purpose intended the anology will suffice. Therefore, the problem is that of finding a suitable reference set and a method of characterizing the set in such a way that each character is uniquely represented.

The available characterization techniques are numerous, and all use an optical scanner, in one way or another, to obtain information about a character. A few of the more successful methods are stroke processing (1), the use of a feature-template preprocessor for feature extraction (6), classification in ad hoc fashion based on strokes, concavities, enclosures and blobs (6), and the Clemens' Technique (6). All of these techniques have had only limited success when applied to nonuniform characters; therefore, the characterizations obtained for each letter were not uniquely recognizable. The method used in this paper was basically a preprocessing of the character to obtain certain information, formulating a mathematical model using the information obtained from preprocessing, and characterization based on the coefficients of a unique model.

Character Preprocessing

Each charcter referred to in this paper was preprocessed by hand. However, the method was the same as one which could be employed by an optical scanner, and as such, the preprocessing technique will be explained from this point of view.

The purpose of preprocessing was to change a particular character into digital data and have this data in a specific format. To do this, the character was scanned to find the uppermost, lowermost, rightmost, and leftmost points in order to set the character boundaries. These boundary lines consisted only of horizontal and vertical lines where any two adjacent lines form a right angle. This had the effect of normalizing the letter to a rectangular area. The rectangle was then subdivided into 64 smaller but equal areas as shown in Figure 1A and these areas were called cells.

To obtain digital information, the cells were assigned values of zero or one depending on the contents of each cell. If a cell contained any part of the character, it was assigned a value of one; otherwise, the cell had a value of zero. The process is shown in Figure 2A, and the resultant was an eight by eight matrix of zeroes and ones.

Next, the matrix was read, and the points were plotted as discrete samples with uniform spacing on an x-y graph (rectangular coordinate graph). Certain letter characteristics could be observed by the particular choice of a starting point and direction of reading. After deliberation over the different symmetrical characteristics of each letter of the alphabet, a method was chosen so that the symmetry of a reference character about a vertical line drawn through the center of the matrix could be observed. The method of reading consisted of starting at cell (1,4) which was the first point, and reading toward the left until cell (1,1) was reached. Then the same procedure was repeated from cell (2,4) to cell (2,1) and repeatedly until cell (8,1)

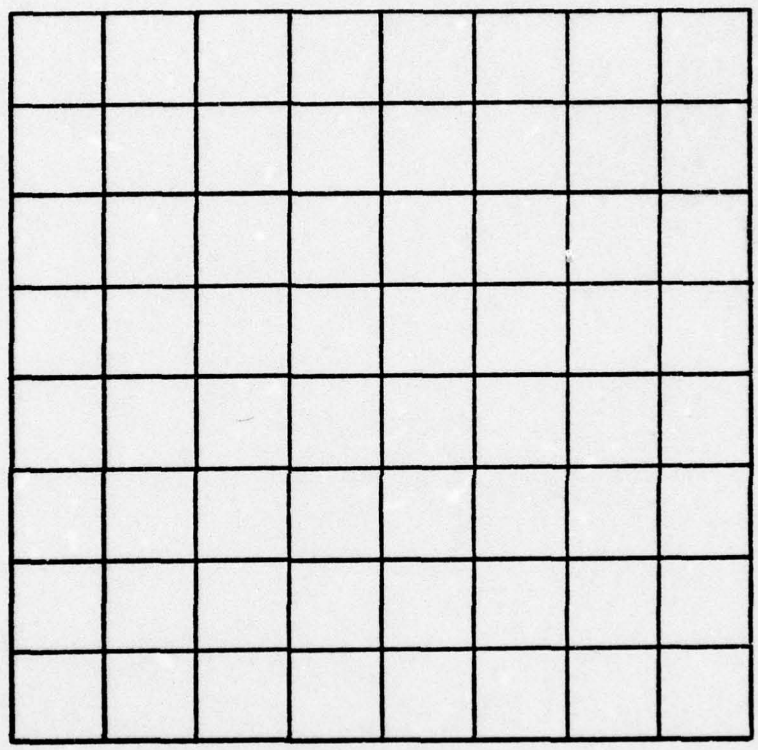


Figure 1A Rectangular Area Subdivided into 64 Cells

0	0	0	1	1	0	0	0
0	0	0	1	1	0	0	0
0	0	1	1	1	1	0	0
0	0	1	0	0	1	0	0
0	1	1	0	0	1	1	0
0	1	1	1	1	1	1	0
1	1	0	0	0	0	1	1
1	0	0	0	0	0	0	1

Figure 2A Eight by Eight Matrix of Zeros and Ones

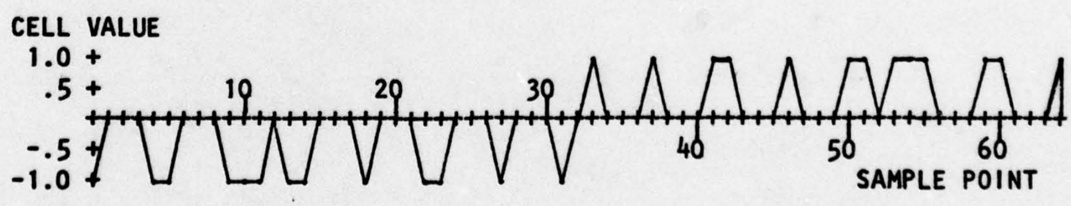


Figure 3A Shifted Waveshape Showing Negative Half-Wave Symmetry

was reached. These points were then plotted parallel to the negative x axis of the x-y graph. The next points to be read were cells (1,5) to (1,8). Then, repeating this left to right movement, cells (2,5) to (2,8) were read. This was done until cell (8,8) had been reached. These points were plotted parallel to the positive x axis on the x-y graph with the first point being cell (1,5).

The result of this method of reading was that it showed a character which was symmetric about a vertical line drawn through the center of the matrix as having half-wave symmetry. However, the characterization of a letter with such symmetry gave a large d. c. component. To avoid this, the half-wave symmetry was changed to negative half-wave symmetry by changing the sign on the points located in the left half plane of the x-y graph. In order to better visualize the shape of the graph, each sample point was connected by a straight line to the next one. Then the resultant waveform was shifted 32 sample points to the right so as to locate the entire wave in the right half plane as shown in Figure 3A.

The final preprocessing step was obtaining data from the x-y graph which will be used in calculating the mathematical model of a letter. This was accomplished by digitally sampling the waveform at 128 equally spaced intervals. The sign of each data point must be preserved.

Mathematical Modeling

The character, at this point, was represented by a particular waveform on an x-y graph. This indicated that the character's x-y plot

may be treated in the same manner as any waveshape, and a Fourier Series could be used to represent it. In general the Fourier Series may be mathematically represented as

$$x(t) = \sum_{j=0}^{\infty} (a_j \cos j\Omega t + \sin j\Omega t) \tag{1}$$

By using the Fourier Series representation, many problems were immediately overcome because of the wealth of information known about it. Also, the series had the very important quality of establishing a unique representation for a given waveform.

However, the calculation of the a_j and b_j coefficients required integration in the continuous time domain as could be seen by the equations

$$a_j = \frac{2}{T} \int_0^T f(t) \cos j\Omega t \, dt \tag{2}$$

$$b_j = \frac{2}{T} \int_0^T f(t) \sin j\Omega t \, dt \tag{3}$$

To avoid this and also be able to use the information already obtained in preprocessing, a Fast Fourier Transform algorithm was used to obtain the harmonic coefficients for the magnitude spectrum. The F. F. T. (Fast Fourier Transform) has many of the same features as the Fourier Series including the uniqueness of representation for a given waveform. Explanation of the F. F. T. algorithm and a subroutine written in Fortran IV are given in Appendix B.

Pattern Recognition

Because of the unique Fourier representation for each reference letter, characterization based upon the coefficients of this representation was the final step. All characterizations obtained in this paper were achieved by manual means. Computer oriented methods are possible and would result in faster and more exact characterizations.

The manual method was as follows. After obtaining the coefficients of the Fourier representation for a particular letter, the magnitudes of the coefficients at each harmonic were calculated as

$$(4) \qquad |RMS*2(k)| = \sqrt{(S(k))^2 + (T(k))^2} \ .$$

These magnitudes were plotted versus the harmonic number as a bar graph. A bar graph of reference letter A is shown in Figure 4A. This same process was used for each reference letter and also for each distorted letter. Next, all of the plots for a particular letter were compared to find consistent similarities. These similarities can be mathematically defined for single harmonics as

$$(5) \qquad \frac{|DC| - |RC|}{|RCF|} \times 100 = \%\ \text{Difference for a Single Harmonic}$$

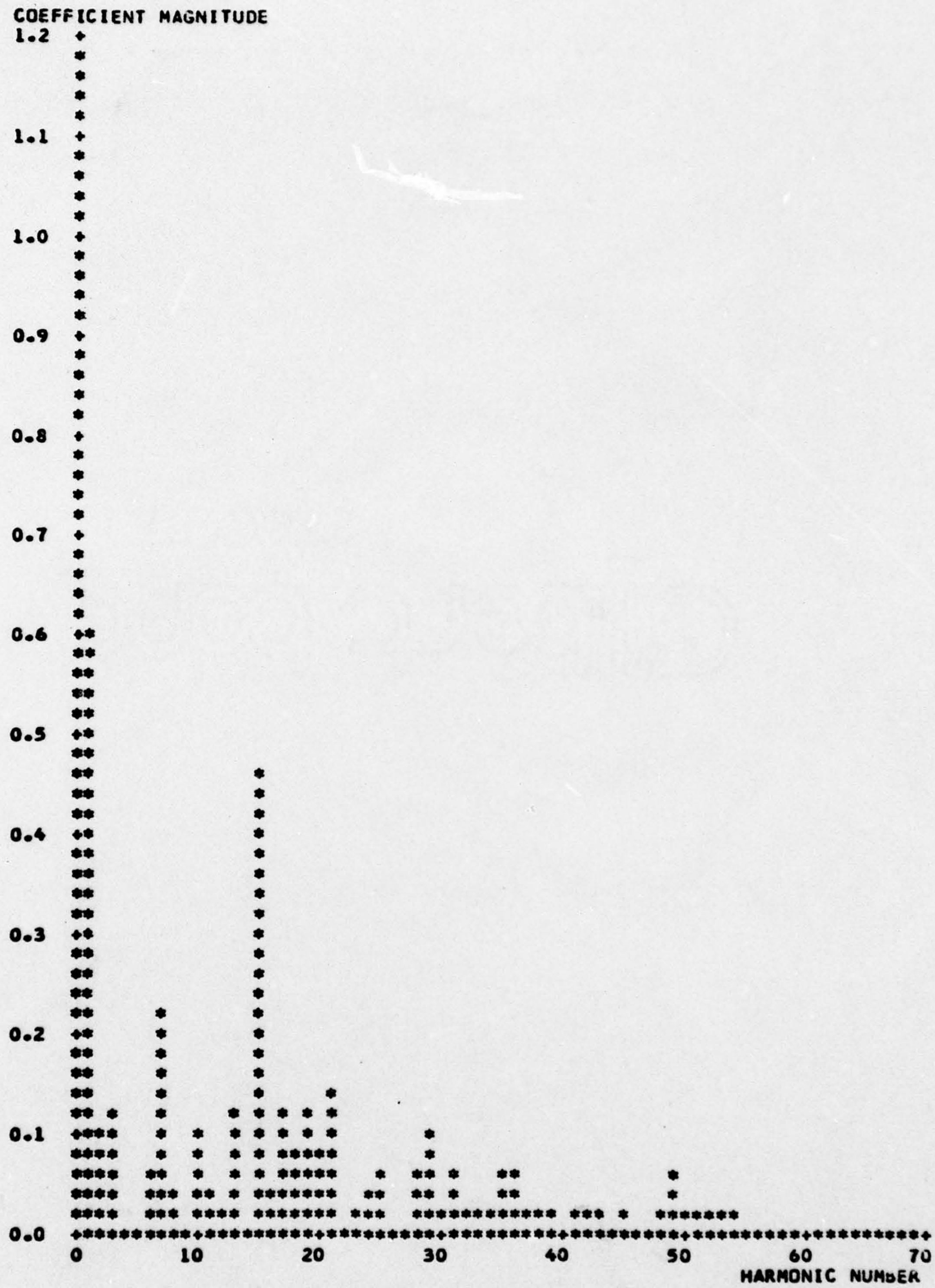


Figure 4A Sample Bar Graph (Magnitude Spectrum)

where $|DC|$ is the coefficient magnitude of the distorted character at a particular harmonic, $|RC|$ is the coefficient magnitude of the reference letter at a specific harmonic, and $|RCF|$ is the coefficient magnitude of the reference letter's fundamental harmonic. In the case of group harmonics, the defining equation is

$$\text{(6)} \qquad \frac{|HMDG| - |HMRG|}{|RFC|} \times 100 = \%\ \text{Difference for Group Harmonics}$$

where $|HMDC|$ is harmonic mean of a particular group in the distorted symbol's magnitude spectrum and $|HMRG|$ is the harmonic mean of a particular group in the reference letter's spectrum. The harmonic mean can be calculated as

$$\text{(7)} \qquad |HM| = \frac{(N_2 - N_1 + 1)}{\sum_{i=N_1}^{N_2} \frac{1}{|x_i|}}$$

where N_1 and N_2 are respectively the left and rightmost harmonics of the group and X_i is magnitude of the ith harmonic. These similarities formed the characterization of the letter. A precaution that no two reference characters have the same representation should be taken. This was especially true for the manual method. As described, the

manual method had many undesirable aspects. However, it served adequately for the purposes of this paper.

A superior method would have been a computer oriented approach. Such a method of pattern recognition would be a necessity if the reading of nonuniform characters were to be handled by a computer. The advantages of using a computer would be in several ways. First, a matrix of higher resolution (having more than 64 cells) could be used which would mean that the fine details of a particular character could be represented. Also, the characterization of a particular reference letter could be carried out to far greater extremes which would decrease the possibility of having the same representation for two reference letters.

There are many techniques already developed that will suffice if the plot (coefficient magnitude versus harmonic) was considered as a picture. If such a consideration was made and since the plot will always be of the same nature, certain techniques could be applied such as a least mean-square error fit (2), derivative data feature extraction (3), use of a contextual analysis and topological coding program (4), or an extension of the manual method used in this paper. Possibly a combination of several methods would be the most advantageous approach.

Chapter 3

DETAILED EXAMINATION OF FOUR CHARACTERS

The hand-printed characters were formed without the use of a straight or guidelines.

Character A

The character A was subjected to four types of distortion. The reference letter A is shown in Figure 5A while the four distorted A characters are shown in Figures 6A, 7A, 8A, and 9A. Comparison of the distorted characters to the reference symbol in a numerical sequence showed a steady increase in the deviation of the characters from the reference. A similar sequential look at Figures 5B through 9B gave more insight into the effects of various distortions. Several interesting points should be noted at this time. First, the width of the stroke used to form a letter seemed to have very little effect upon the matrix except in the cases of extremely broad or narrow widths where these might cause parts of the letter to become obscured. Secondly, visual inspection of the matrices showed that although character symmetry was lost the letter was still easily recognizable in most cases. Also, at this point it should be noted that in the normalization of script character A, the head and foot finals (5) have been eliminated. By thinking of these strokes as only letter connections in script-written text, the elimination of them was justified because they added little or nothing to the character recognition process. Upon close inspection of the script A matrix

in Figure 9B, one would also notice that the letter which this matrix defined was not recognizable within the matrix as the other A characters were.

A sequential comparison of each character's matrix with the resulting waveform was next. Figures 5C through 9C are the waveshapes. From this comparison, the symmetry of the A reference character about a vertical line drawn through the center of its matrix could be observed. Another observation made was the fact that as a letter was shifted more to one side, this same side of the matrix had an increase in the ratio of valued cells to zero cells. This increase could be seen in the waveshape as a shifting of area. Next, by looking only at the waveform of each of the characters, a distinct similarity between most of them could be seen.

However, the heart of this analysis lay in the magnitude spectrum of each of the characters. Figures 5D through 9D show the bar graphs. As stated earlier, the characterization of a reference letter was contained in the similarities of these magnitude spectra. There were no indepth computer comparisons made of the bar graphs because of the limited distortions and with only visually-obvious similarities being noted. These similarities included the strict magnitude at a specific harmonic, the magnitude relative to nearest neighbors at a specific harmonic, combinations of strict and relative magnitude changes in a group, and general shape of the bar graph.

The characterization of reference letter A was made without regard to script character A. The reason for disregarding the A script

symbol could best be seen in a comparison of its matrix and waveshape to the matrix and waveshape of the reference character. Although both characters were known to be the letter A, the matrix for the script A did not have enough resolution to allow the symbol to be recognizable in it. This being the case, the Fourier representation of the matrix could not be used in forming the characterization for the reference A.

An increase in resolution could be accomplished only if several facts were kept in mind. The first one was that the number of positive and negative lobes in the waveform was directly related to the number of rows in the matrix, and increasing the number of rows would negate any useful characterization information already obtained. So the increase in resolution should be accomplished by increasing the number of columns which only increases the number of data points and the emphasis on small details in the character. However, because of the severe distortion in the script A character, such an increase in the number of columns still could not catch enough detail to allow character recognition based on the reference A. In order to obtain character recognition of such a letter, a minimum matrix of 32 by 32 would have to be used in characterizing the reference set.

For reference symbol A, the following characterization was made. Harmonic numbers 15, 27, 30, 34, and 49 were chosen as the similar single harmonics. By referring to Table 1A, the largest percent difference could be seen to be almost 17 percent which was for harmonic 15 of the slanted A and the hand-printed A. Harmonic numbers

A

Figure 5A Reference Character A

0	0	0	1	1	0	0	0
0	0	0	1	1	0	0	0
0	0	1	1	1	1	0	0
0	0	1	1	1	1	0	0
0	1	1	0	0	1	1	0
0	1	1	1	1	1	1	0
1	1	0	0	0	0	1	1
1	1	0	0	0	0	1	1

Figure 5B Matrix for Reference Character A

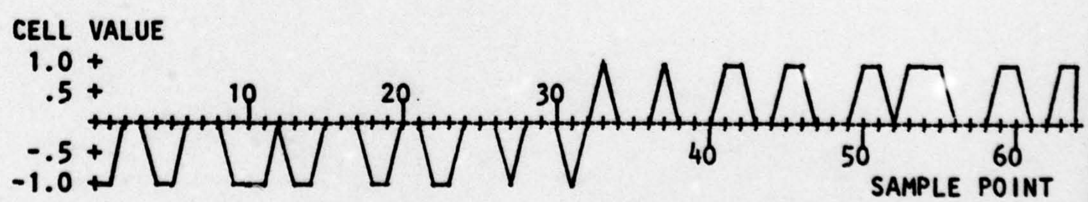


Figure 5C Waveshape for Reference Character A

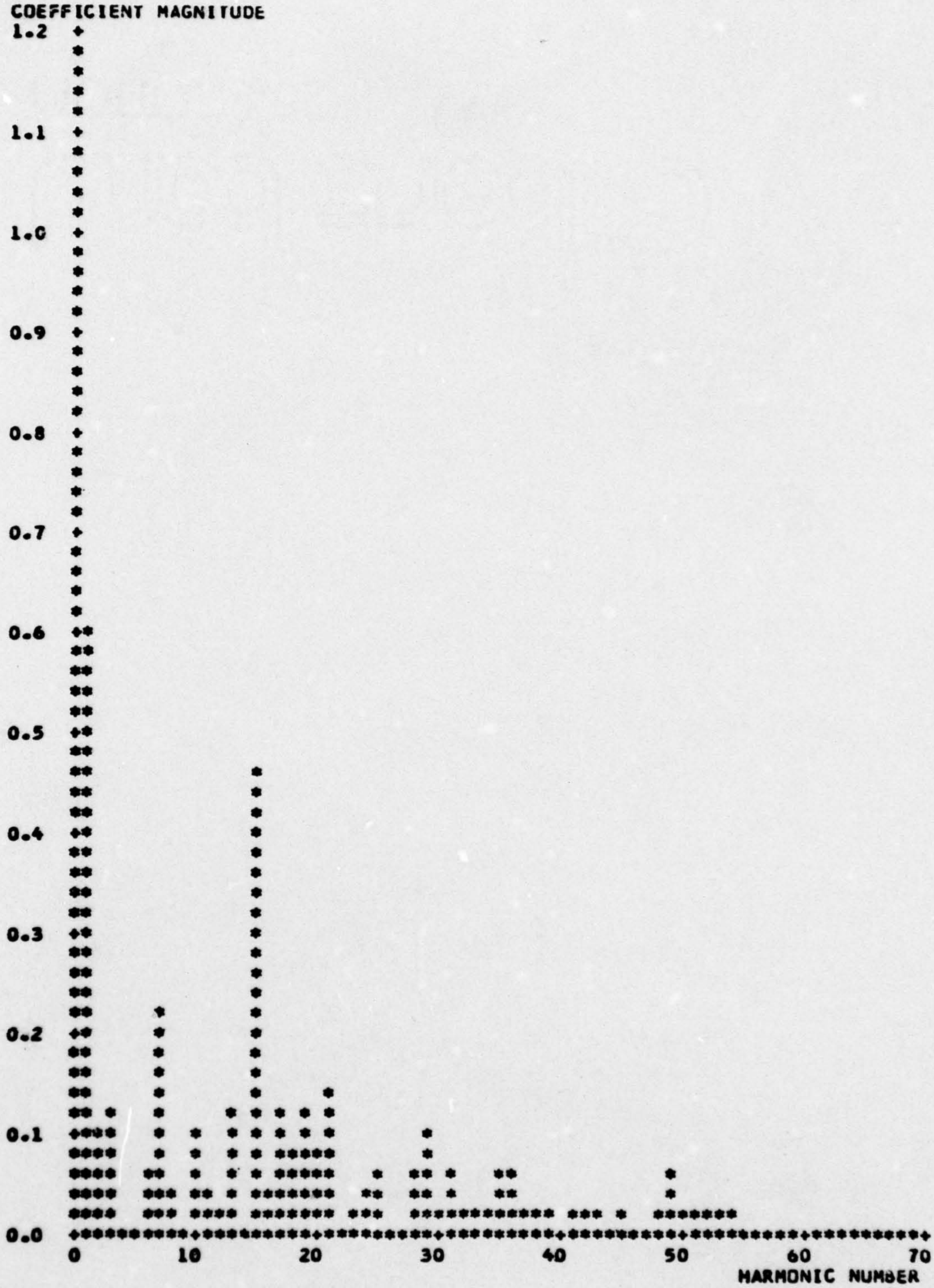


Figure 5D Magnitude Spectrum for Reference Character A

A

Figure 6A Light Character A

0	0	0	1	1	0	0	0
0	0	0	1	1	0	0	0
0	0	1	1	1	1	0	0
0	0	1	0	0	1	0	0
0	1	1	1	1	1	1	0
0	1	1	1	1	1	1	0
1	1	0	0	0	0	1	1
1	0	0	0	0	0	0	1

Figure 6B Matrix for Light Character A

Figure 6C Waveshape for Light Character A

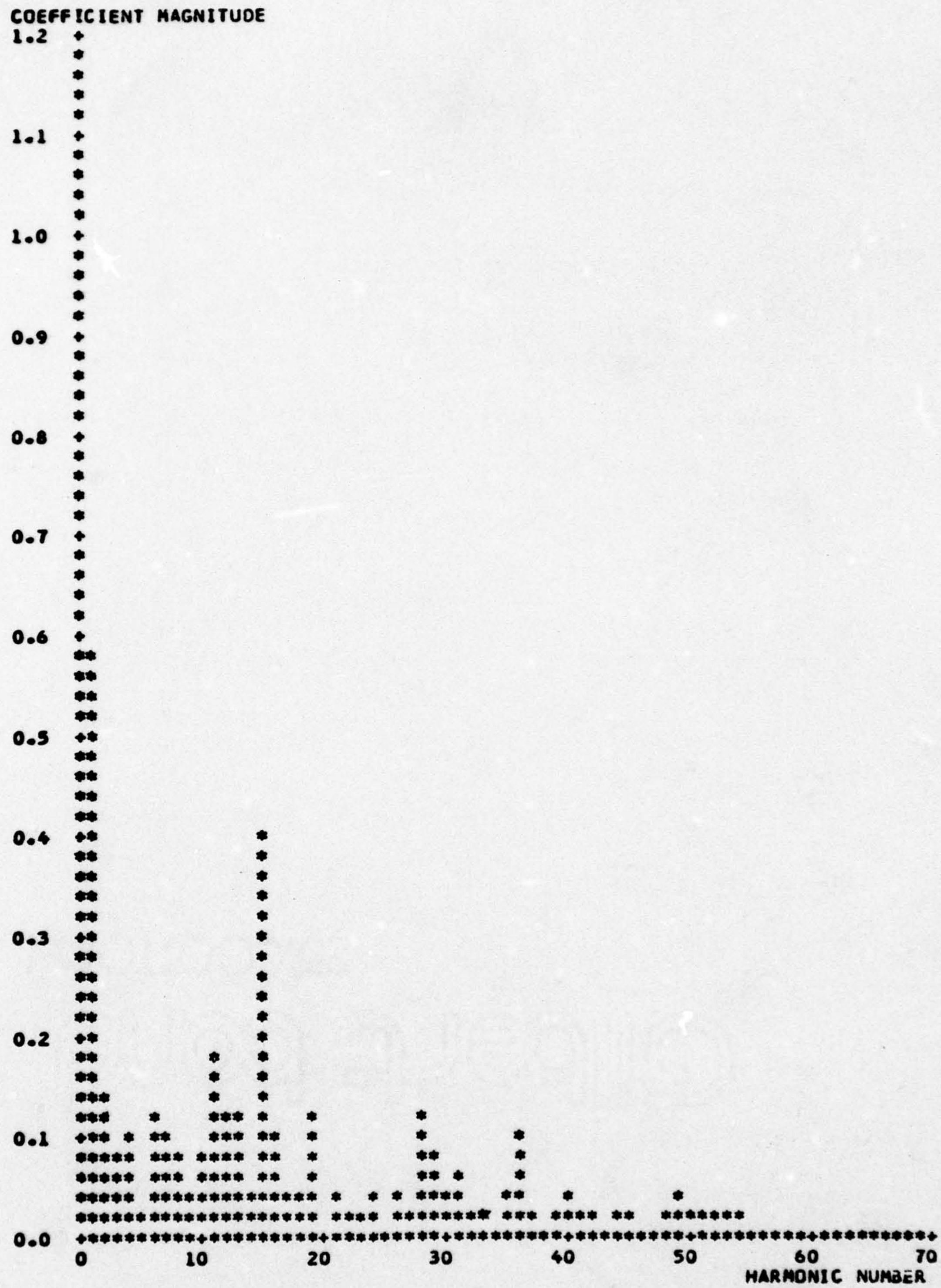


Figure 6D Magnitude Spectrum for Light Character A

Figure 7A Slanted Character A

0	0	0	1	1	1	1	0
0	0	1	1	1	1	1	0
0	0	1	1	1	1	1	0
0	1	1	1	1	1	1	1
0	1	1	1	0	1	1	1
1	1	1	1	1	1	1	1
1	1	1	1	1	1	1	1
1	1	1	0	0	1	1	1

Figure 7B Matrix for Slanted Character A

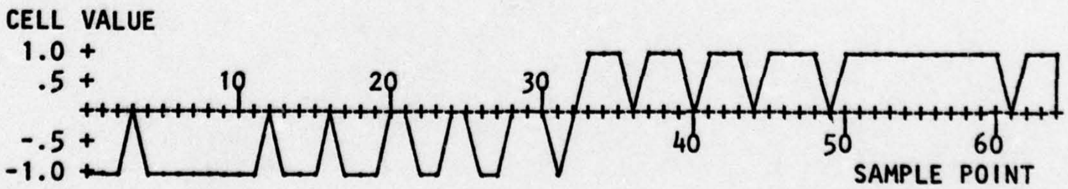


Figure 7C Waveshape for Slanted Character A

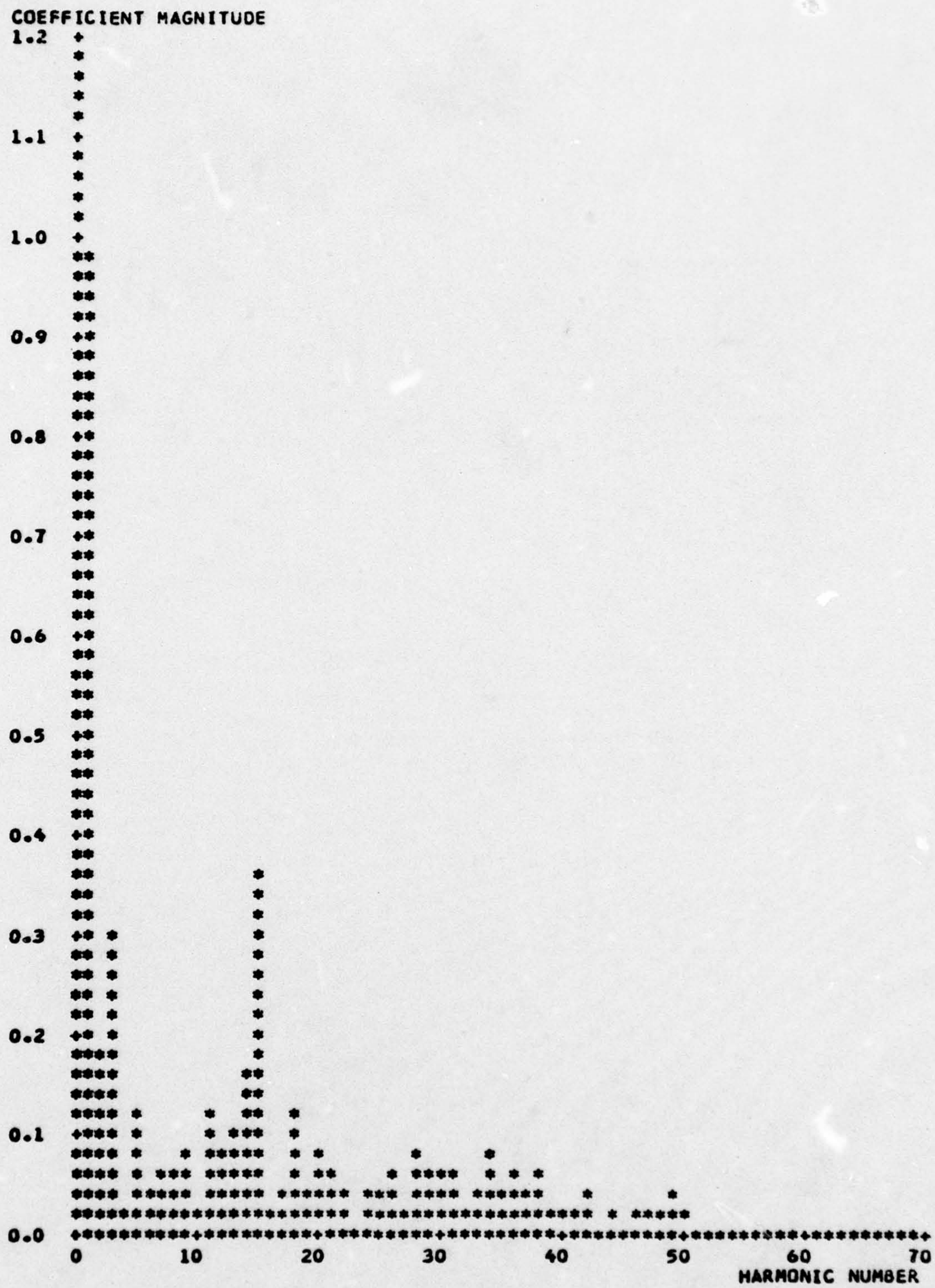


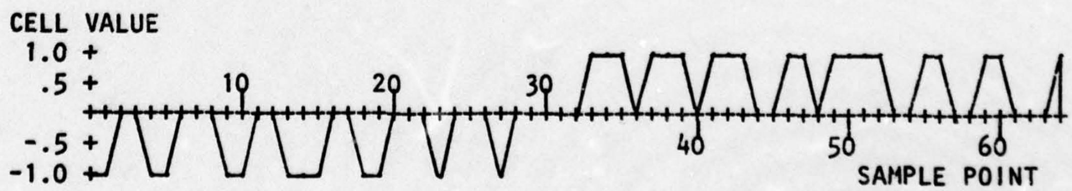
Figure 7D Magnitude Spectrum for Slanted Character A

A

Figure 8A Hand-Written Character A

0	0	0	0	1	1	1	0
0	0	0	1	1	1	1	0
0	0	0	1	1	1	1	0
0	0	1	1	0	1	1	0
0	1	1	1	1	1	1	1
0	1	1	0	0	0	1	1
1	1	0	0	0	0	1	1
1	1	0	0	0	0	0	1

Figure 8B Matrix for Hand-Written Character A



Figuer 8C Waveshape for Hand-Written Character A

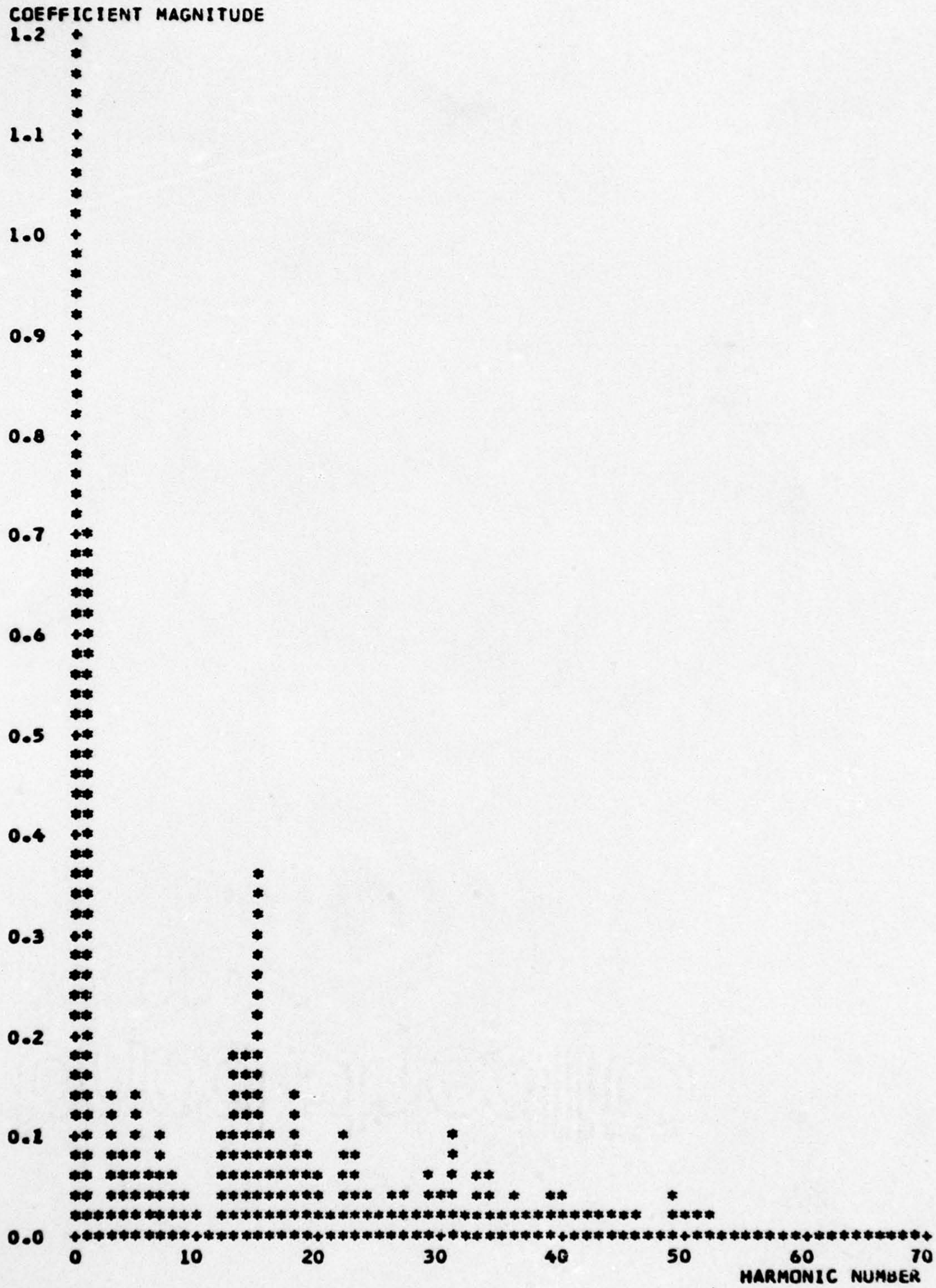


Figure 8D Magnitude Spectrum for Hand-Written Character A

Figure 9A Script Character A

0	0	0	0	0	0	1	1
0	0	0	0	0	1	1	1
0	0	0	0	1	1	1	0
0	0	0	0	1	1	1	0
0	0	1	1	1	1	0	0
0	0	1	1	1	0	0	0
0	1	1	1	1	0	0	0
1	1	1	0	1	0	0	0

Figure 9B Matrix for Script Character A

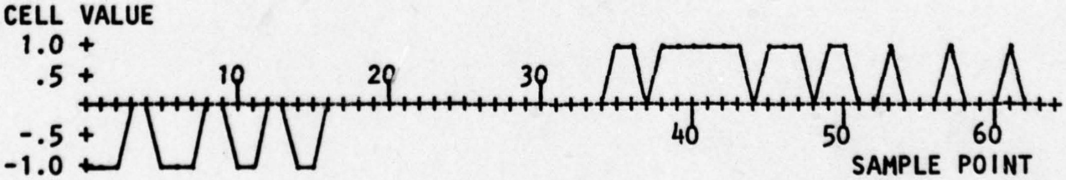


Figure 9C Waveshape for Script Character A

Figure 9D Magnitude Spectrum for Script Character A

Table 1A

Percent Difference between the Characterizing
Single Harmonics of the Distorted
and Reference A Letters

Har.	IDCI				IRCI	Percent Difference			
	1	2	3	4		1	2	3	4
15	0.04	0.36	0.36	0.08	0.46	10.0	16.7	16.7	63.3
27	0.02	0.02	0.04	0.04	X	2.5	2.5	5.8	5.8
30	0.04	0.06	0.04	0.06	0.02	3.3	6.7	3.3	6.7
34	X	0.08	0.06	0.02	0.02	2.5	10.0	6.7	0.0
49	0.04	0.04	0.04	X	0.06	3.3	3.3	3.3	9.2

Key

Column 1 refers to the Light character
Column 2 refers to the Slanted Character
Column 3 refers to the Hand-Printed Character
Column 4 refers to the Script Character
X implies a Bar Graph value of zero but for calculation
purposes a value of .005 is assumed

Table 1B

Percent Difference between the Characterizing Group Harmonics of the Distorted and Reference A Letters

Har.	IHMDGI				IHMRGI	Percent Difference			
	1	2	3	4		1	2	3	4
1-3	0.14	0.30	0.05	0.19	0.15	1.7	25.0	16.7	6.7
18-21	0.02	0.06	0.05	0.05	0.10	13.3	6.7	8.3	8.3
41-47	0.01	0.01	0.01	0.02	0.01	0.0	0.0	0.0	1.7
54-63	0.01	0.01	0.01	0.01	0.01	0.0	0.0	0.0	0.0

Key

Column 1 refers to the Light Character
Column 2 refers to the Slanted Character
Column 3 refers to the Hand-Printed Character
Column 4 refers to the Script Character

1 through 3, 18 through 21, 41 through 47, and 54 through 63 were chosen as the similar group harmonics. By referring to Table 1B, the largest percent difference could be seen to be almost 17 percent which was for the group 1 through 3 of the hand-printed A. Since no indepth analysis was obtained, the visual appearance of the bar graphs was very important. By this criteria the magnitude spectra of letters showed a large amount of resemblance.

Character E

The character E was subjected to four types of distortion. The reference character E is shown in Figure 10A, and the four distorted E characters are shown in figures 11A, 12A, 13A, and 14A. A comparison in numerical sequence of the reference character to the distorted letters showed a steady increase in the deviation of the distorted characters from the reference. A similar sequential look at Figures 10B through 14B allowed a better understanding of the effects of various distortions. At this time several points should be noted. First, the stroke width used to form a letter had little or no effect on the matrix except in the extreme cases noted for character A. Secondly, visual inspection of the matrices showed that although the physical geometry of a letter was altered, the character was still recognizable. It should also be noted that there was no need for letter truncation as experienced with character A. Because of this and the fact that the script character E was recognizable in its defining matrix, the script character was used in the character recognition of the reference set.

A sequential comparison of each character's matrix with the resulting waveform was next. Figures 10C through 14C are the waveshapes. From this comparison, a distinct feature of printed characters as opposed to script characters was observed. The printed character showed its basic use of straight vertical and horizontal lines as single large areas of the x-y graph where as the curved formations of the script E showed up as smaller, more numerous areas, provided the resolution of the matrix was adequate.

However, the bar graph of each character more fully described the outcome. Figures 10D through 14D show the magnitude spectra. As stated earlier, the characterization of a reference character was determined by the similarities of its bar graph and those of the distorted characters. The same criteria was used for this letter as was used for character A.

The following characterization for reference letter E was made. Harmonic numbers 2, 5, 11, 26, 28, 34, 37 and 39 were chosen as the similar single harmonics. By referring to Table 2A, the largest percent difference could be seen to be almost 32 percent which was for the fifth harmonic of the script E. This large percent difference seemed to be caused by the head and foot finals on the script E. Harmonic numbers 7 through 9, 17 and 18, 34 through 40, and 44 through 63 were chosen as the similar group harmonics. By referring to Table 2B, the largest percent difference could be seen to be almost 28 percent which was for the group 7 through 9 of the light E. An examination of the magnitude spectra of the light and reference E

E

Figure 10A Reference Character E

1	1	1	1	1	1	1	1
1	1	0	0	0	0	0	0
1	1	0	0	0	0	0	0
1	1	1	1	1	1	1	1
1	1	1	1	1	1	1	1
1	1	0	0	0	0	0	0
1	1	0	0	0	0	0	0
1	1	1	1	1	1	1	1

Figure 10B Matrix for Reference Character E

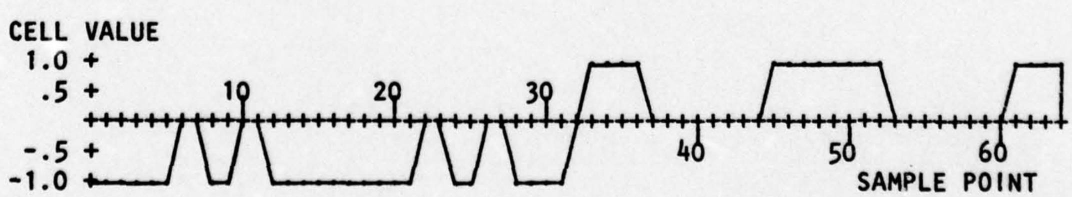


Figure 10C Waveshape for Reference Character E

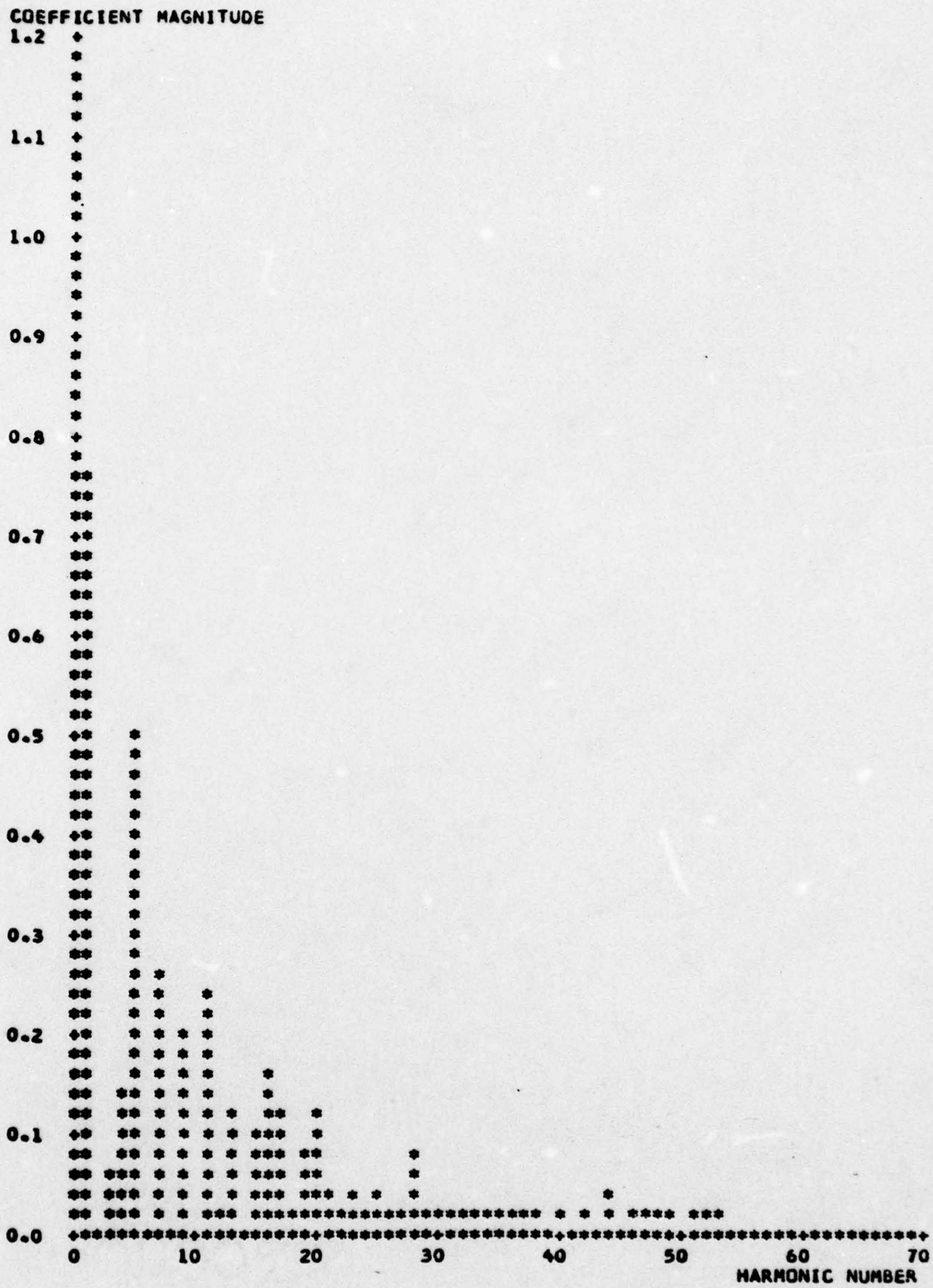


Figure 10D Magnitude Spectrum for Reference Character E

Figure 11A Light Character E

1	1	1	1	1	1	1	1
1	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0
1	1	1	1	1	1	1	1
1	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0
1	1	1	1	1	1	1	1

Figure 11B Matrix for Light Character E

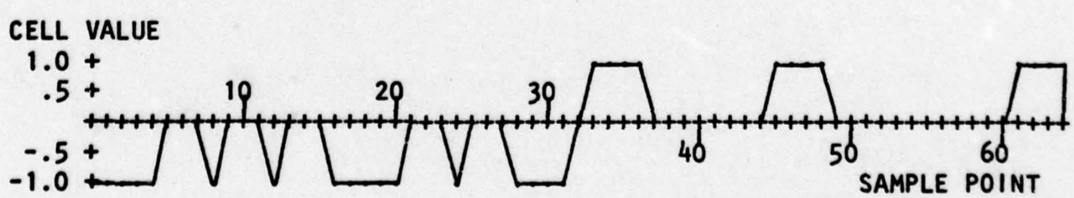


Figure 11C Waveshape for Light Character E

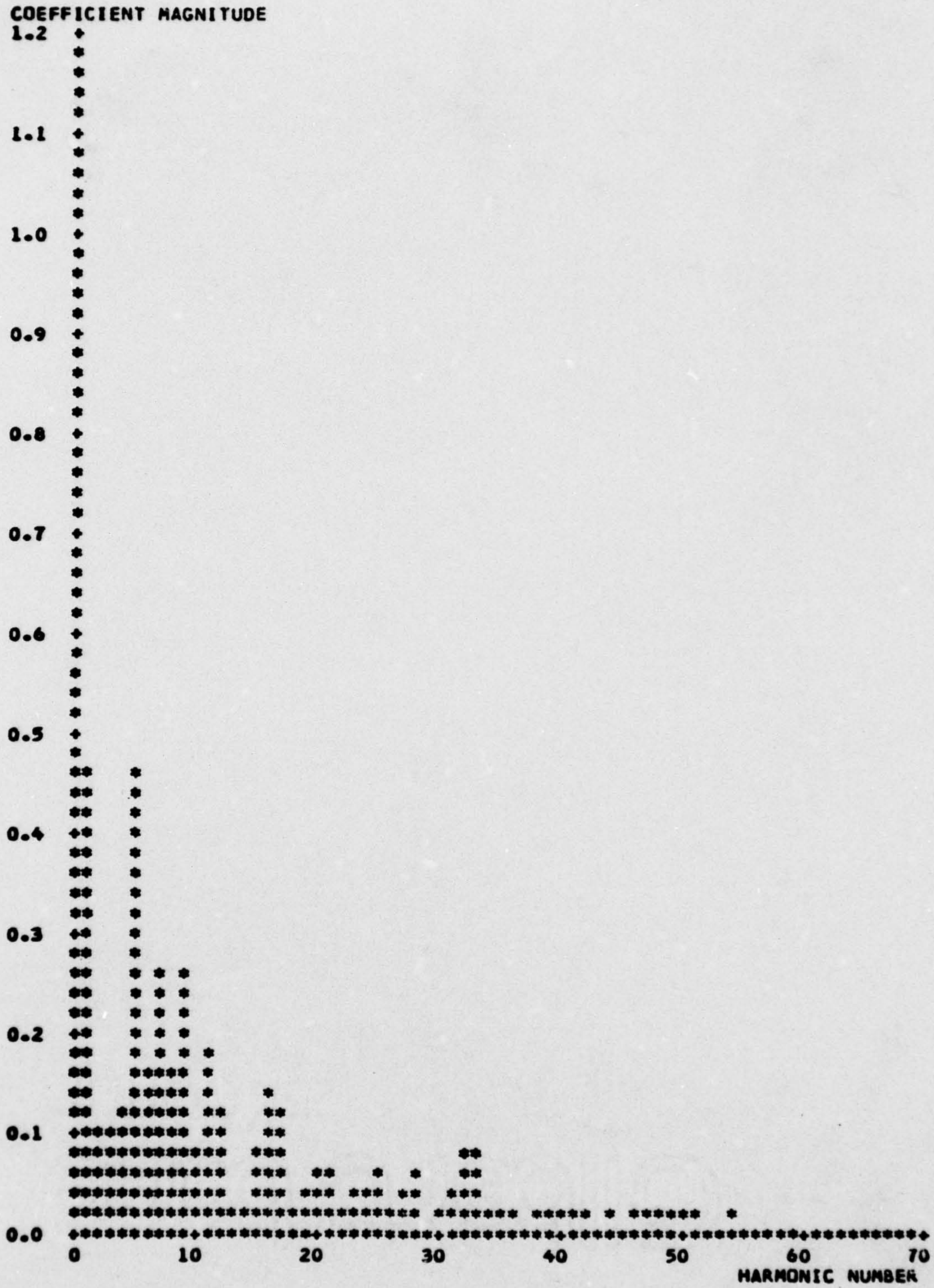


Figure 11D Magnitude Spectrum for Light Character E

Figure 12A Slanted Character E

0	1	1	1	1	1	1	1
0	1	1	1	1	1	1	1
0	1	1	1	0	0	0	0
1	1	1	1	1	1	1	1
1	1	1	1	1	1	1	1
1	1	1	1	0	0	0	0
1	1	1	1	1	1	1	0
1	1	1	1	1	1	1	0

Figure 12B Matrix for Slanted Character E

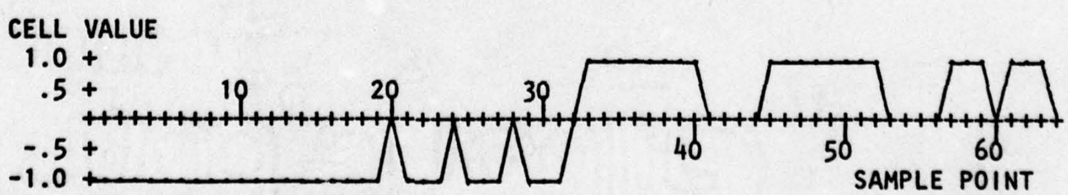


Figure 12C Waveshape for Slanted Character E

Figure 12D Magnitude Spectrum for Slanted Character E

Figure 13A Hand-Written Character E

1	1	1	1	1	1	1	1
1	1	0	0	0	0	0	0
1	1	0	0	0	0	0	0
1	1	1	1	1	1	0	0
1	1	1	1	1	1	0	0
1	1	0	0	0	0	0	0
1	1	0	0	0	0	0	0
1	1	1	1	1	1	1	0

Figure 13B Matrix for Hand-Written Character E

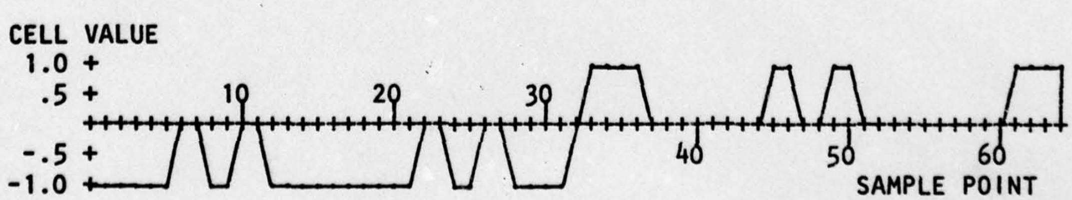


Figure 13C Waveshape for Hand-Written Character E

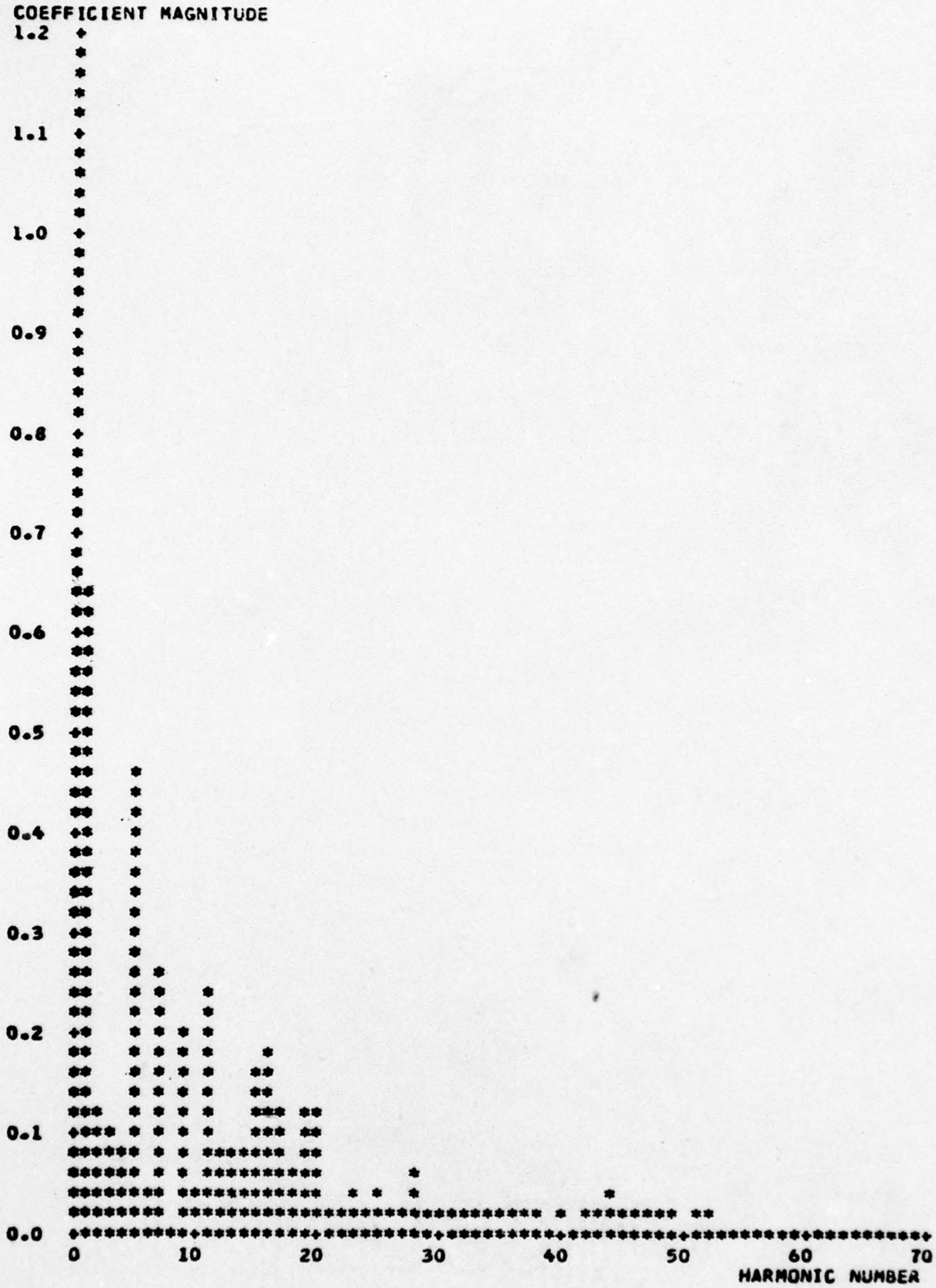


Figure 13D Magnitude Spectrum for Hand-Written Character E

Figure 14A Script Character E

0	0	0	0	1	1	1	1
0	0	0	1	1	1	0	1
0	0	0	1	1	0	1	1
0	0	1	1	1	0	1	0
0	1	1	1	1	0	0	0
1	1	0	0	0	1	0	0
1	1	0	0	1	1	0	0
1	1	1	1	1	0	0	0

Figure 14B Matrix for Script Character E

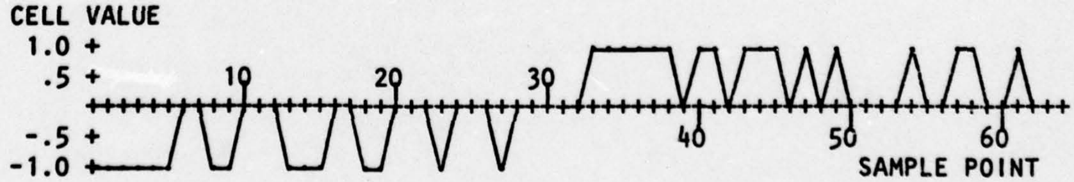


Figure 14C Waveshape for Script Character E

Figure 14D Magnitude Spectrum for Script Character E

Table 2A

Percent Difference between the Characterizing Single Harmonics of the Distorted and Reference E Letters

Har.	IDCI				IRCI	Percent Difference			
	1	2	3	4		1	2	3	4
2	0.10	0.08	0.12	0.04	X	12.5	9.9	15.1	4.6
5	0.46	0.42	0.46	0.26	0.50	5.3	10.5	5.3	31.6
11	0.18	0.20	0.24	0.10	0.24	7.9	5.3	0.0	18.4
26	0.02	0.02	0.02	0.04	0.02	0.0	0.0	0.0	2.6
28	0.06	0.06	0.06	0.10	0.08	2.6	2.6	2.6	2.6
34	0.02	0.04	0.02	0.04	0.02	0.0	2.6	0.0	2.6
37	X	0.02	0.02	0.04	0.02	2.0	0.0	0.0	2.6
39	0.02	X	X	X	X	2.0	0.0	0.0	0.0

Key

Column 1 refers to the Light Character
Column 2 refers to the Slanted Character
Column 3 refers to the Hand-Printed Character
Column 4 refers to the Script Character
X implies a Bar Graph value of zero but for calculation purposes a value of .005 is assumed

Table 2B

Percent Difference between the Characterizing Group Harmonics of the Distorted and Reference E Letters

Har.	IHMDGI				IHMRGI	Percent Difference			
	1	2	3	4		1	2	3	4
7-9	0.22	0.04	0.01	0.04	0.01	27.6	3.9	0.0	3.9
17-18	0.03	0.06	0.08	0.07	0.03	0.0	3.9	6.6	5.3
34-40	0.01	0.01	0.01	0.01	0.01	0.0	0.0	0.0	0.0
44-63	0.01	0.01	0.01	0.01	0.01	0.0	0.0	0.0	0.0

Key

Column 1 refers to the Light Character
Column 2 refers to the Slanted Character
Column 3 refers to the Hand-Printed Character
Column 4 refers to the Script Character

symbols showed that the large difference was due exclusively to the eighth harmonic of the light E. However, because there was such a great visual resemblance between the bar graphs of the letters, the characterization was not changed.

Character R

Character R was subjected to four types of distortion. The reference character R is shown in Figures 15A while the four distorted R letters are shown in Figures 16A, 17A, 18A, and 19A. By comparing the distorted letters to the reference symbol in a numerical sequence, an increase in deviation of each character from the reference was seen. A similar comparison of Figures 15B through 19B gave a better understanding of the effects caused by various distortions.

Several interesting points could be noted at this time. First, as with the two previous characters, varying the width of the stroke used to form a character seemed to have very little effect on the defining matrix unless the width was carried to an extreme as in Figure 17B. Secondly, as the letter was slanted to one side, there was a resultant shift in area of the waveshape. At this point it should be noted that in the normalization of script symbol R, the head and foot finals (5) have been eliminated as was the case for script letter A. The same justifications that were used for script A were used here for script R character truncation. Also, upon inspection of the matrix in Figure 19B, one would note that the letter which this matrix defined was not recognizable within the matrix.

A sequential comparison of each character's matrix with the resulting waveshape was next. Figures 15C through 19C are the

R

Figure 15A Reference Character R

1	1	1	1	1	1	1	0
1	1	0	0	1	1	1	0
1	1	0	0	0	1	1	0
1	1	1	1	1	1	1	0
1	1	1	1	1	1	0	0
1	1	1	1	1	1	0	0
1	1	0	0	1	1	1	0
1	1	0	0	0	1	1	1

Figure 15B Matrix for Reference Character R

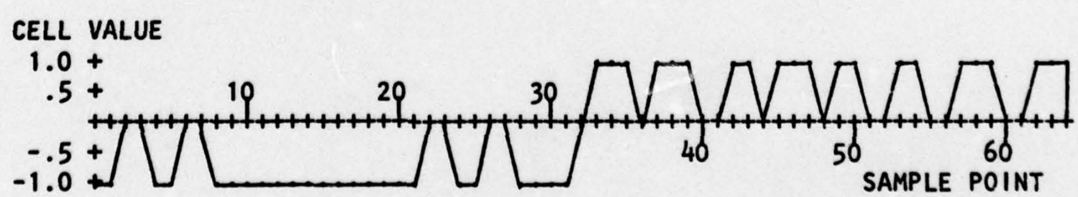


Figure 15C Waveshape for Reference Character R

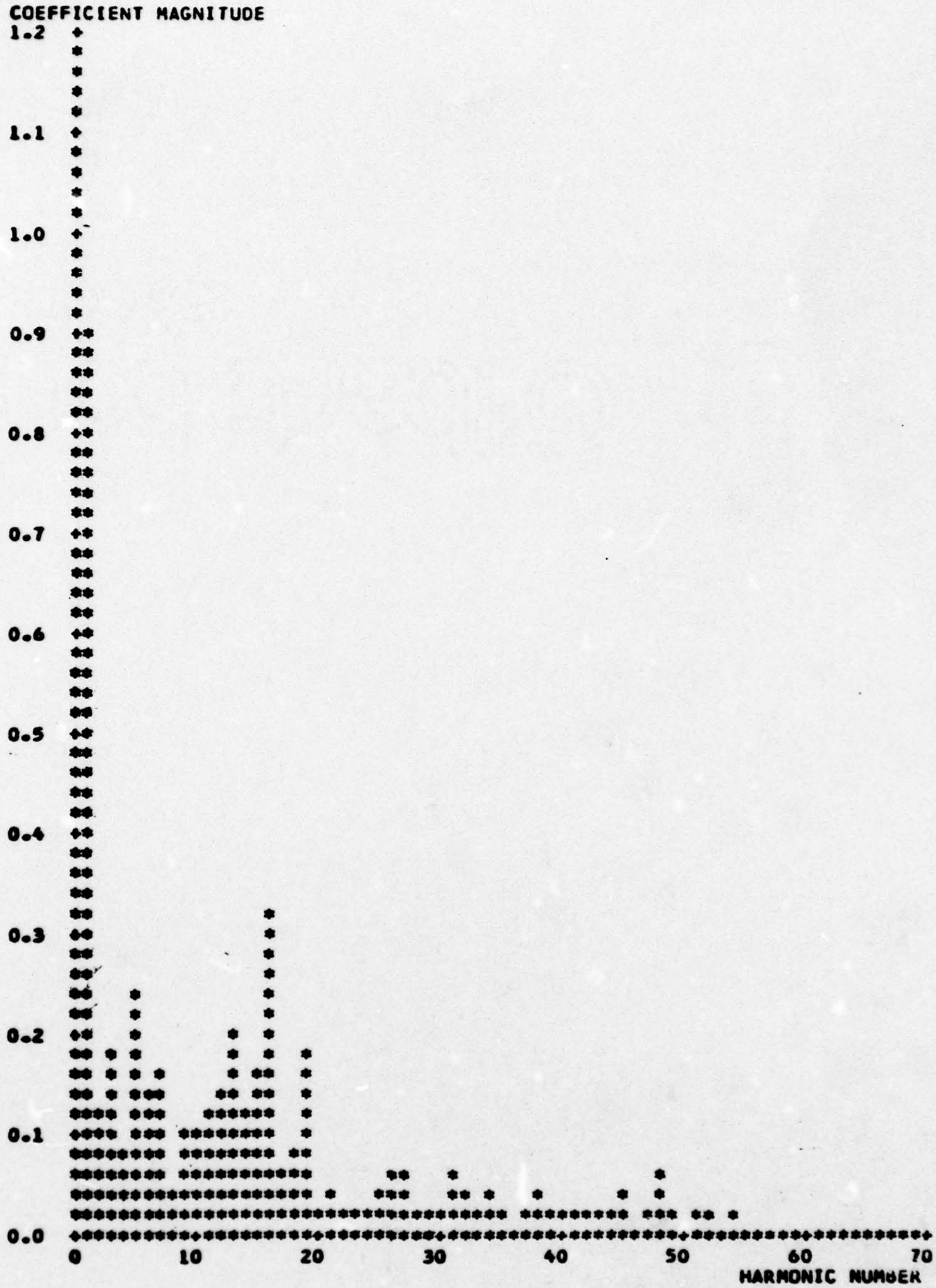


Figure 15D Magnitude Spectrum for Reference Character R

R

Figure 16A Light Character R

1	1	1	1	1	1	1	0
1	0	0	0	0	1	1	0
1	0	0	0	0	1	1	0
1	1	1	1	1	1	1	0
1	1	1	1	0	0	0	0
1	0	0	1	1	1	0	0
1	0	0	0	1	1	1	0
1	0	0	0	0	1	1	1

Figure 16B Matrix for Light Character R

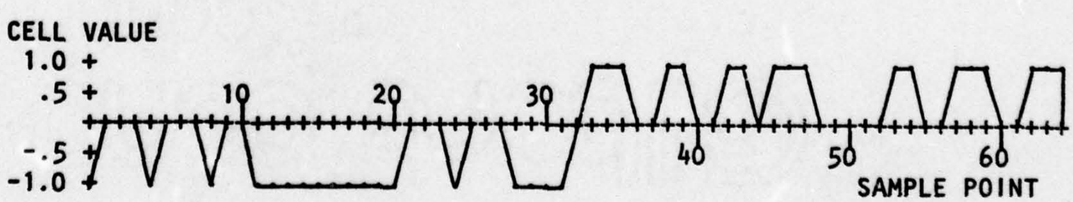


Figure 16C Waveshape for Light Character R

Figure 16D Magnitude Spectrum for Light Character R

Figure 17A Slanted Character R

0	1	1	1	1	1	1	1
1	1	1	1	1	1	1	1
1	1	1	1	0	1	1	1
1	1	1	1	1	1	1	1
1	1	1	1	1	1	1	1
1	1	1	1	1	1	1	0
1	1	1	1	1	1	1	1
1	1	1	0	1	1	1	1

Figure 17B Matrix for Slanted Character R

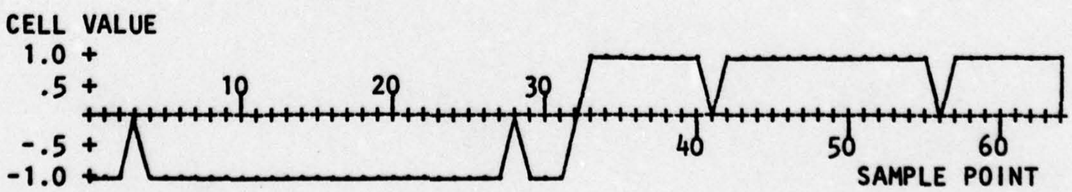


Figure 17C Waveshape for Slanted Character R

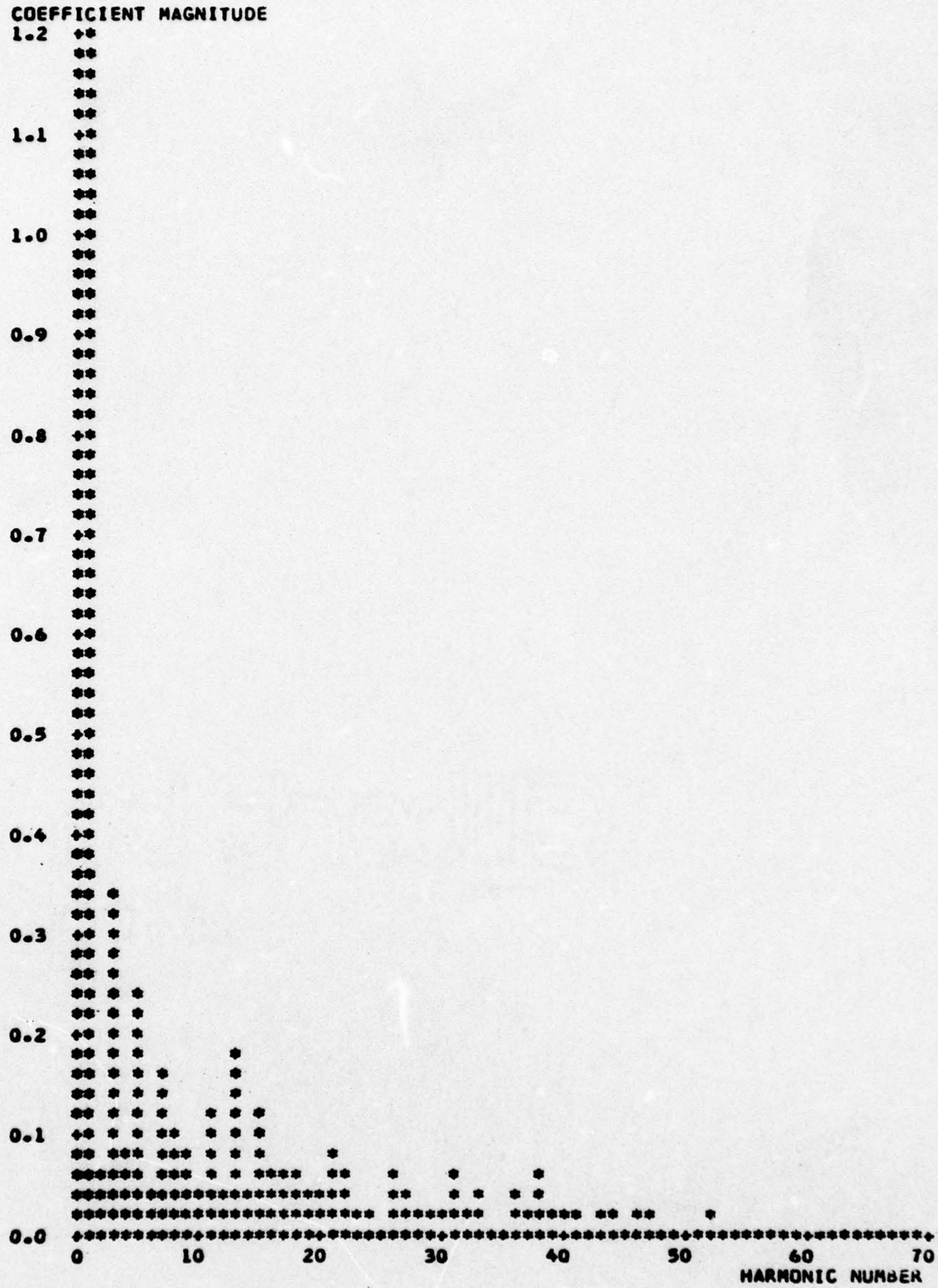


Figure 17D Magnitude Spectrum for Slanted Character R

Figure 18A Hand-Written Character R

0	1	1	1	1	1	1	0
0	1	0	0	0	0	1	1
1	1	0	0	0	0	1	1
1	1	0	0	0	1	1	0
1	1	1	1	1	1	0	0
1	1	0	1	1	1	0	0
1	1	0	0	1	1	1	0
1	1	0	0	0	0	1	1

Figure 18B Matrix for Hand-Written Character R

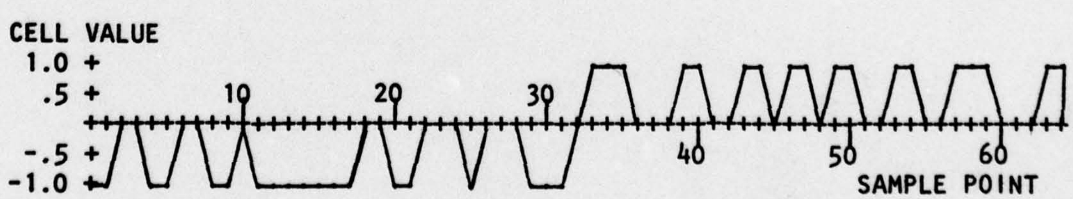


Figure 18C Waveshape for Hand-Written Character R

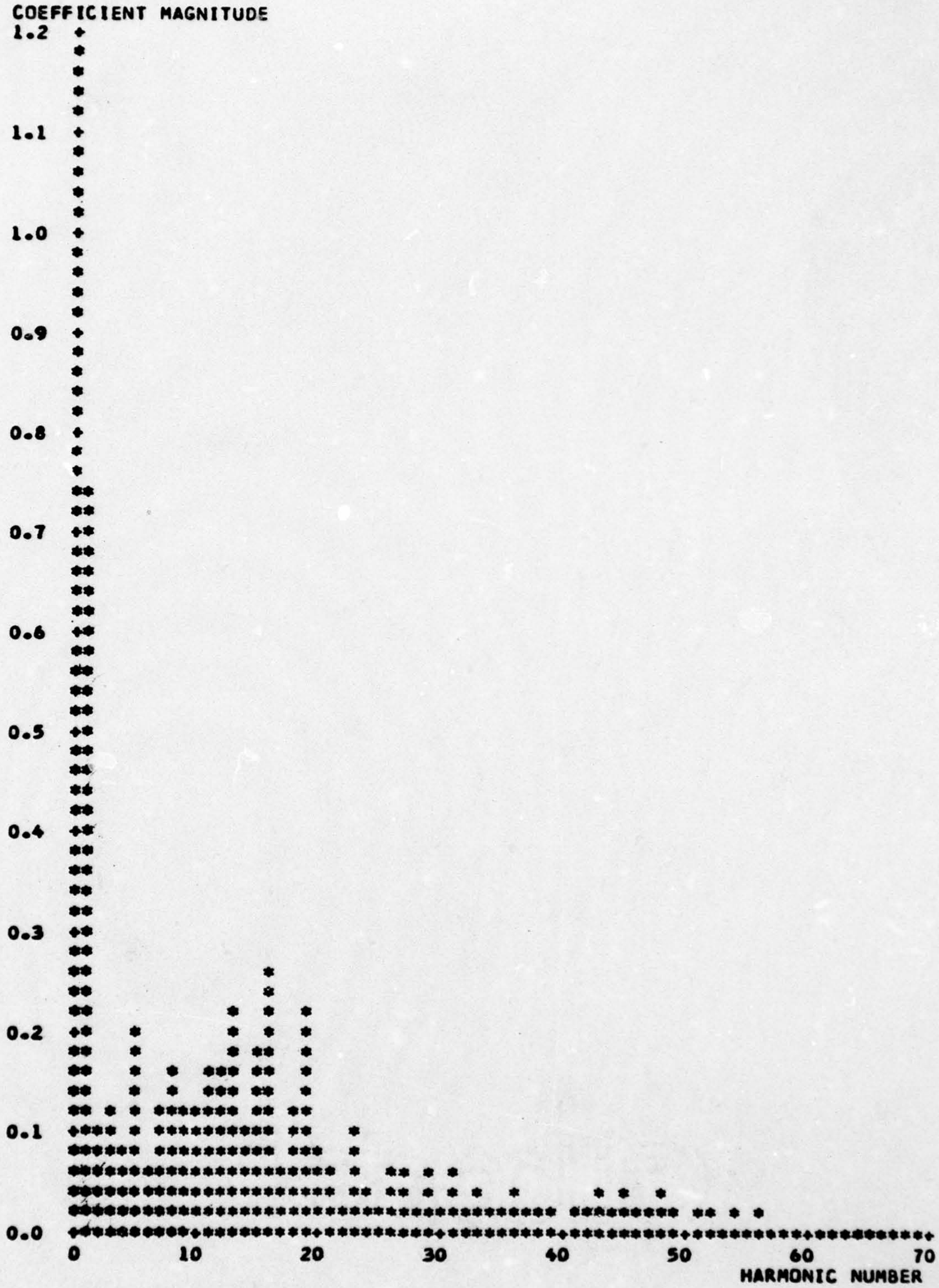


Figure 18D Magnitude Spectrum for Hand-Written Character R

Figure 19A Script Character R

0	0	0	0	0	0	1	1
0	0	0	0	0	1	1	1
0	0	0	0	1	1	1	0
0	0	0	0	1	1	1	0
0	0	1	1	1	1	0	0
0	0	1	1	1	0	0	0
0	1	1	1	1	0	0	0
1	1	1	0	1	0	0	0

Figure 19B Matrix for Script Character R

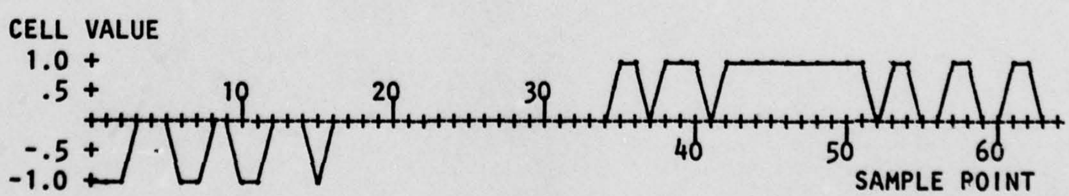


Figure 19C Waveshape for Script Character R

Figure 19D Magnitude Spectrum for Script Character R

Table 3A

Percent Difference between the Characterizing
Single Harmonics of the Distorted
and Reference R Letters

Har.	IDCI				IRCI	Percent Difference			
	1	2	3	4		1	2	3	4
2	0.20	0.06	0.10	0.20	0.12	8.9	6.7	2.2	8.9
9	0.08	0.08	0.12	0.06	0.10	2.2	2.2	2.2	4.4
30	0.02	0.02	0.02	0.04	0.02	0.0	0.0	0.0	2.2
40	0.02	0.02	X	0.04	0.02	0.0	0.0	1.7	2.2

key

Column 1 refers to the Light Character
Column 2 refers to the Slanted Character
Column 3 refers to the Hand-Printed Character
Column 4 refers to the Script Character
X implies a Bar Graph value of zero but for calculation
purposes a value of .005 is assumed

Table 3B

Percent Difference between the Characterizing Group Harmonics of the Distorted and Reference R Letters

Har.	IHMDGI				IHMRGI	Percent Difference			
	1	2	3	4		1	2	3	4
3-6	0.19	0.09	0.09	0.05	0.14	5.6	5.6	5.6	10.0
16-19	0.10	0.05	0.12	0.04	0.11	1.1	6.7	1.1	7.8
24-27	0.02	0.01	0.04	0.03	0.04	2.2	3.3	0.0	1.1
43-46	0.01	0.01	0.03	0.01	0.01	0.0	0.0	2.2	0.0
48-63	0.01	0.01	0.01	0.01	0.01	0.0	0.0	0.0	0.0

Key

Column 1 refers to the Light Character
Column 2 refers to the Slanted Character
Column 3 refers to the Hand-Printed Character
Column 4 refers to the Script Character

waveforms. In this comparison the distortion due to a large increase in the width of the stroke was very apparent in Figure 17C. However, the slant R character was still clearly visible in its defining matrix. But in the case of the script R, a comparison showed that the matrix was unable to define the letter, and thus, its magnitude spectrum was not used in the characterization.

Figures 15D through 19D show the bar graphs and following the same guidelines as used previously, the characterization of reference letter R was determined. Harmonic numbers 2, 9, 30, and 40 were chosen as the similar single harmonics. The largest percent difference as seen from Table 3A was almost 9 percent which was for the second harmonic of the light R character. Harmonic numbers 3 through 6, 16 through 19, 24 through 27, 43 through 46, and 48 through 63 were chosen as the similar group harmonics. The largest percent difference was almost 7 percent as shown in Table 3B for the 16 through 19 group of harmonics of the slanted R letter. An interesting point should be noted at this time about the percent differences of the script R character. In most all cases its difference was larger respectively than for any other letter. This showed that the magnitude spectrum of the script R was not one which could be recognized as representing an R.

Character S

Reference letter S and the four distorted S characters are shown in Figures 20A through 24A. A comparison in numerical sequence of the distorted letters to the reference symbol showed a steady increase in the deviation of each distorted character from the

reference. A similar review of Figures 20B through 24B showed the effects of each distortion.

Here again the stroke width used seemed to have little effect on the matrix except in extreme cases such as Figure 22B. Although the slant S character was clearly distinguishable as the equivalent of the reference S symbol, the slant S letter was barely definable in its matrix. Although this was the case, the slant S's magnitude spectrum was still used in the characterization of the reference S letter. Visual inspection of the other matrices showed that with limited geometrical letter distortion the other S characters could still be recognized in their defining matrix. When comparing Figures 24A and 24B, it should be noted that no symbol truncation was necessary for the script character S. Because of the fact that the script S was recognizable in its defining matrix, the symbol was used in the characterization of the reference letter.

A comparison of each character's matrix with the resulting waveform was next. The waveshapes are pictured in Figures 20C through 24C. This comparison showed the nature of curved symbols as opposed to the straight line composed letters viewed until now. The semicircular composition of the S was not recognizable in the waveshapes so even if an S were composed of straight horizontal and vertical lines, it would still appear the same. This means that a symbol did not have to be a smooth evenly contoured stroke; instead, it could consist of short continuous straight lines and still be readily recognized.

For the characterization of the S reference letter, Figures 20D through 24D, which show the bar graphs, was used. Also, the same criteria which was used for the previous characters was used for this symbol.

For reference symbol S, the following characterization was made. Harmonic numbers 2, 9, 21, 24, 32, and 40 were chosen as the similar single harmonics. The largest percent difference as shown in Table 4A was slightly more than 10 percent. This occurred for the ninth harmonic of the script S character. Harmonic numbers 3 through 5, 11 and 12, 29 through 31, and 44 through 63 were chosen as the similar group harmonics. The largest percent difference as shown in Table 4B was almost 26 percent which was for the 3 through 5 group of harmonics for the script S letter. It was interesting to note at this time that the greatest percent differences did not occur in the slanted S letter, although this particular symbol was barely recognizable in its defining matrix. Also, the overall visual appearance of the distorted and reference letter's bar graphs have a close resemblance.

S

Figure 20A Reference Character S

0	1	1	1	1	1	1	1
1	1	1	0	0	1	1	1
1	1	1	1	0	0	0	0
0	1	1	1	1	1	1	0
0	0	0	1	1	1	1	1
0	0	0	0	0	0	1	1
1	1	1	0	0	1	1	1
1	1	1	1	1	1	1	1

Figure 20B Matrix for Reference Character S

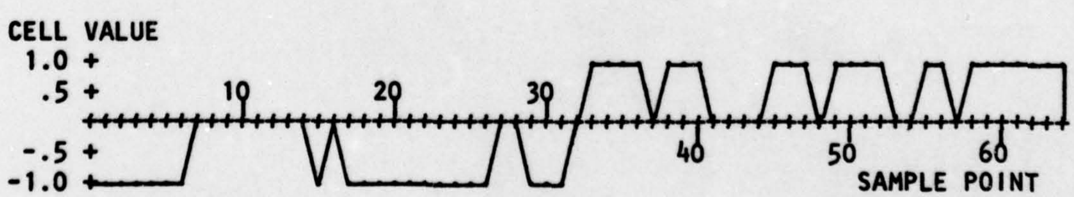


Figure 20C Waveshape for Reference Character S

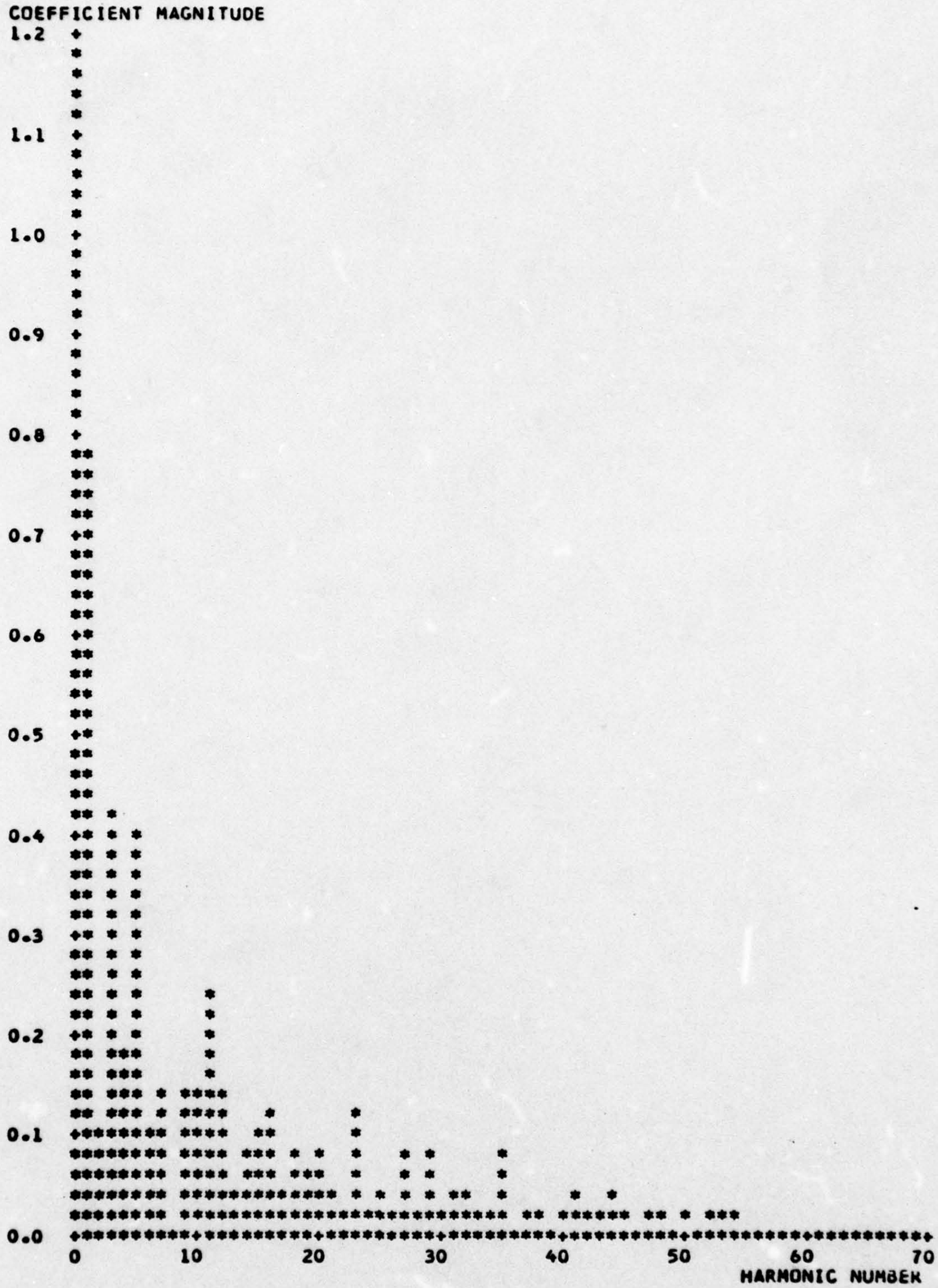


Figure 20D Magnitude Spectrum for Reference Character S

S

Figure 21A Light Character S

1	1	1	1	1	1	1	0
1	1	0	0	0	0	1	0
1	1	0	0	0	0	0	0
0	1	1	1	1	1	0	0
0	0	0	0	1	1	1	1
0	0	0	0	0	0	1	1
1	1	0	0	0	0	1	1
1	1	1	1	1	1	1	1

Figure 21B Matrix for Light Character S

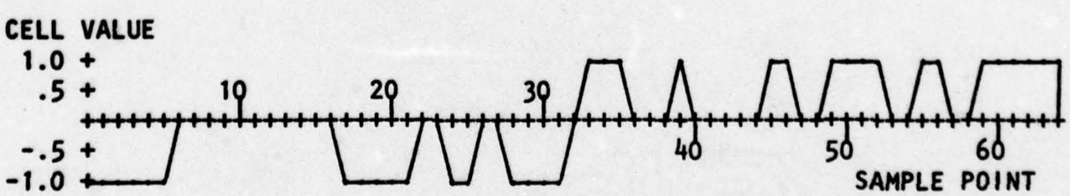


Figure 21C Waveshape for Light Character S

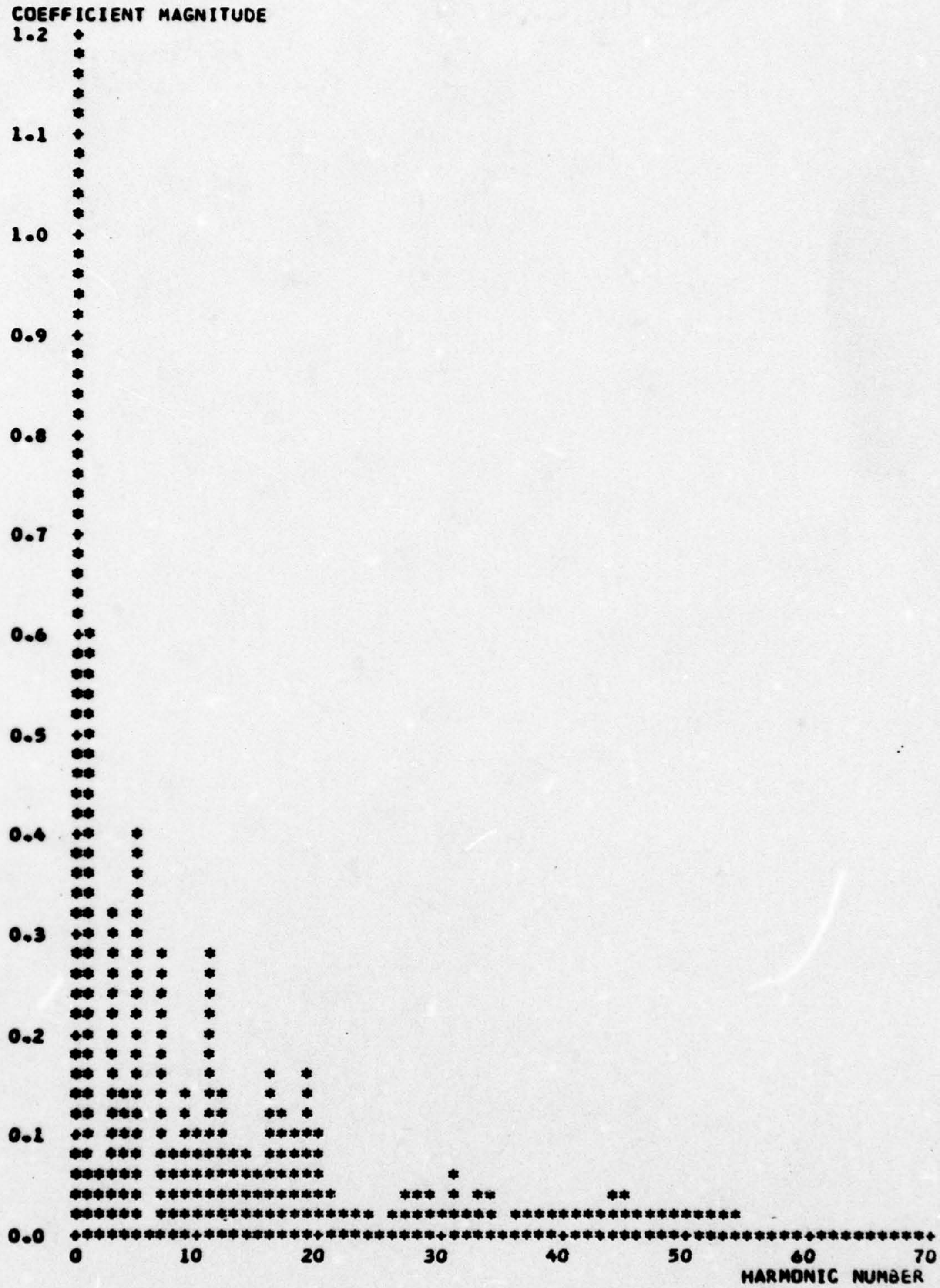


Figure 21D Magnitude Spectrum for Light Character S

Figure 22A Slanted Character S

0	0	1	1	1	1	1	1
0	1	1	1	1	1	1	1
0	1	1	1	1	0	1	0
0	1	1	1	1	1	1	1
0	0	1	1	1	1	1	1
1	1	1	0	1	1	1	1
1	1	1	1	1	1	1	1
1	1	1	1	1	1	1	0

Figure 22B Matrix for Slanted Character S

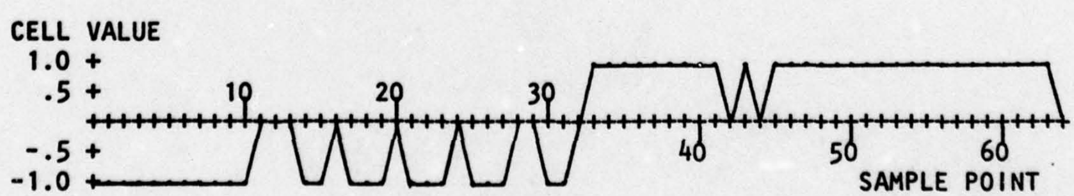


Figure 22C Waveshape for Slanted Character S

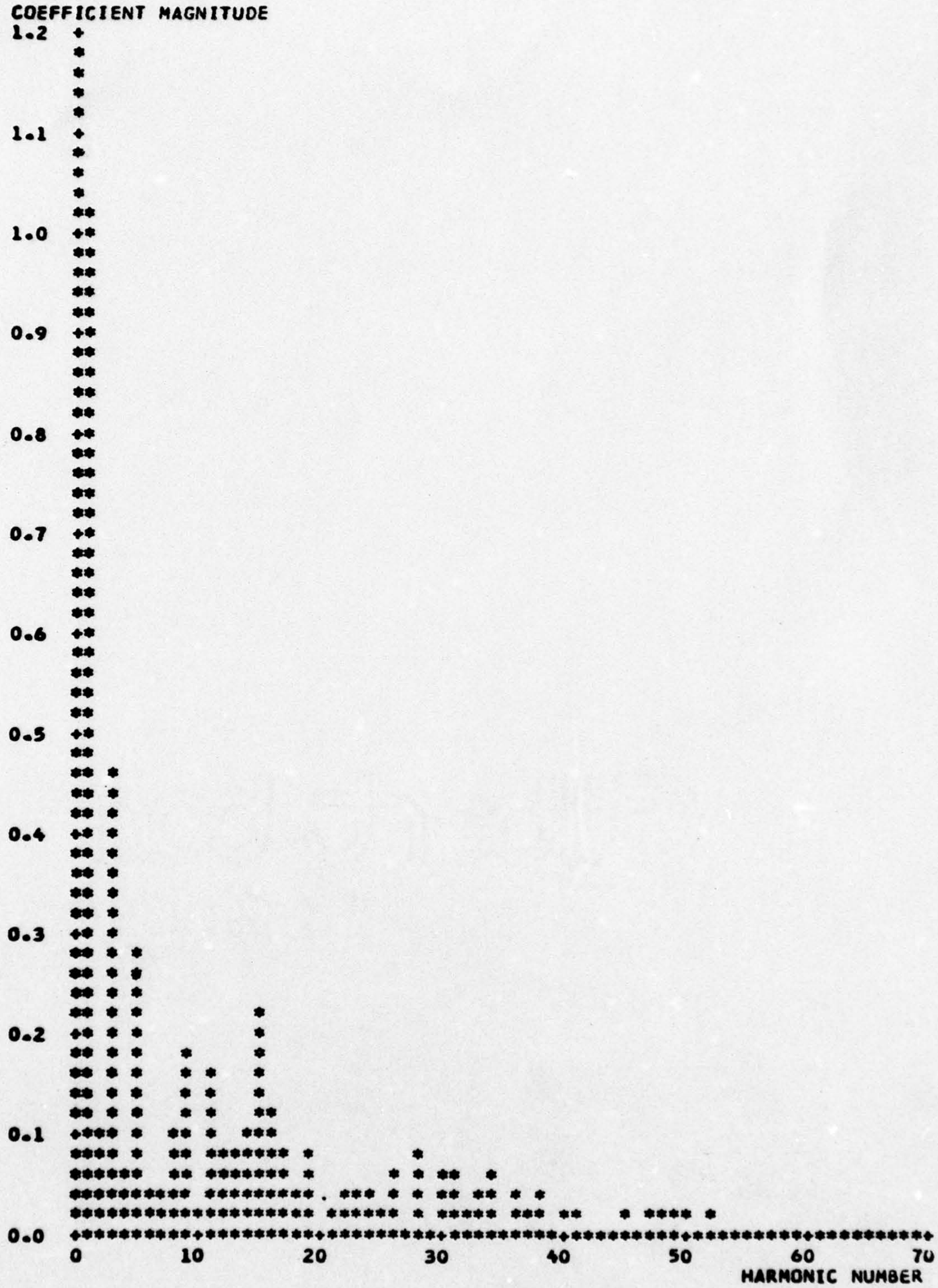


Figure 22D Magnitude Spectrum for Slanted Character S

Figure 23A Hand-Written Character S

0	0	1	1	1	1	1	1
0	1	1	1	0	0	0	0
0	1	1	1	0	0	0	0
0	0	1	1	1	1	0	0
0	0	0	0	1	1	1	0
0	0	0	0	0	1	1	0
0	0	0	0	0	1	1	0
1	1	1	1	1	1	1	0

Figure 23B Matrix for Hand-Written Character S

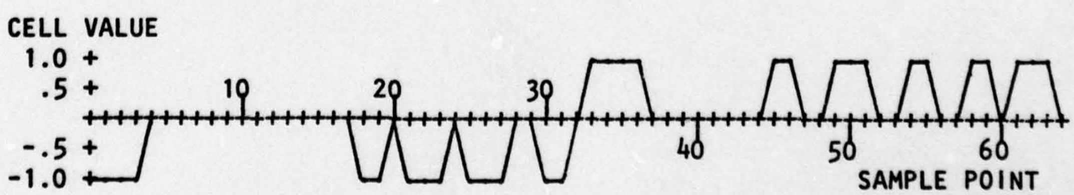


Figure 23C Waveshape for Hand-Written Character S

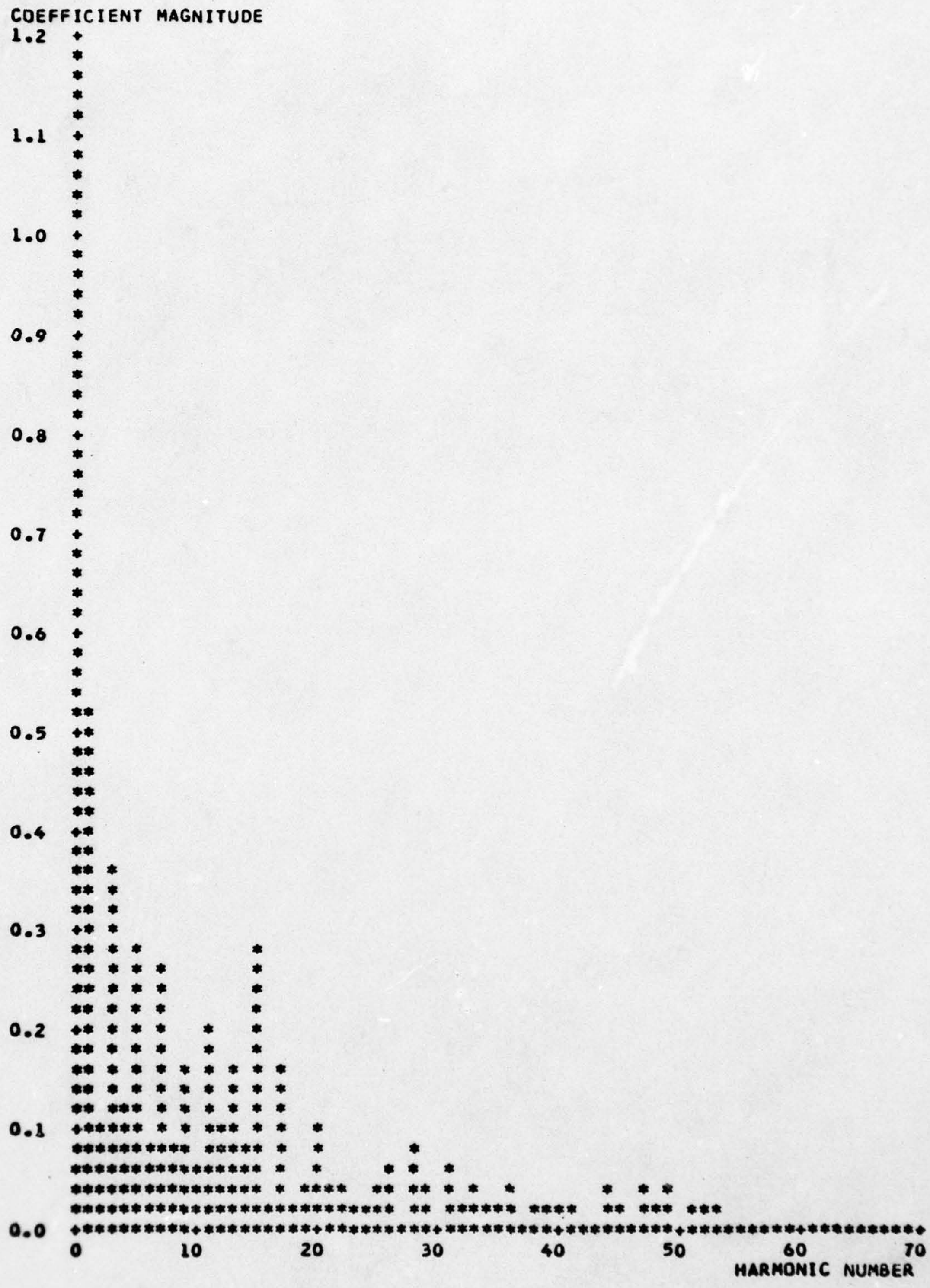


Figure 23D Magnitude Spectrum for Hand-Written Character S

Figure 24A Script Character S

0	0	0	0	1	1	1	1
0	0	0	1	1	0	0	1
0	0	0	1	1	0	1	1
0	0	0	1	1	1	0	0
1	1	0	0	1	1	0	0
1	0	0	0	1	1	0	0
1	0	0	0	1	1	0	0
1	1	1	1	1	0	0	0

Figure 24B Matrix for Script Character S

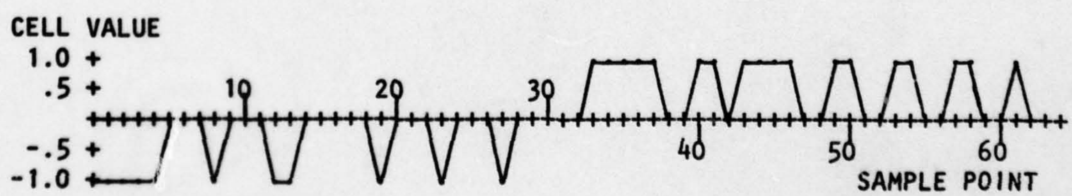


Figure 24C Waveshape for Script Character S

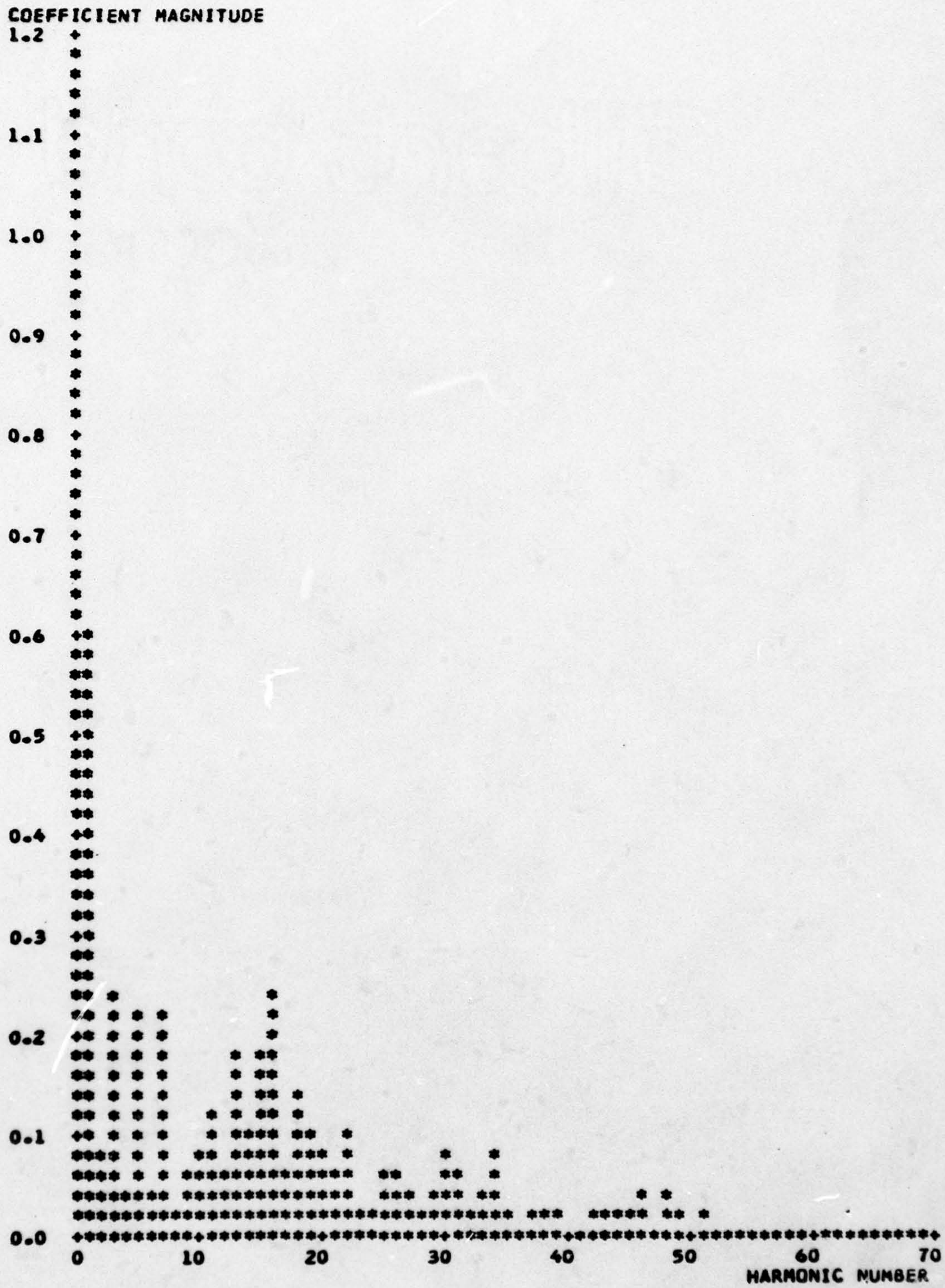


Figure 24D Magnitude Spectrum for Script Character S

Table 4A

Percent Difference between the Characterizing Single Harmonics of the Distorted and Reference S Letters

Har.	IDCI				IRCI	Percent Difference			
	1	2	3	4		1	2	3	4
2	0.06	0.10	0.10	0.08	0.10	5.1	0.0	0.0	2.6
9	0.14	0.18	0.16	0.06	0.14	0.0	5.1	2.6	10.3
21	0.04	0.02	0.04	0.06	0.04	0.0	2.3	0.0	2.3
24	0.02	0.04	0.02	0.02	0.02	0.0	2.3	0.0	0.0
32	0.02	0.02	0.02	0.02	0.04	2.3	2.3	2.3	2.3
40	0.02	0.02	0.02	X	0.02	0.0	0.0	0.0	1.9

Key

Column 1 refers to the Light Character
Column 2 refers to the Slanted Character
Column 3 refers to the Hand-Printed Character
Column 4 refers to the Script
X implies a Bar Graph value of zero but for calculation purposes a vaule of .005 is assumed

Table 4B

Percent Difference between the Characterizing Group Harmonics of the Distorted and Reference S Letters

Har.	IHMDGI				IHMRGI	Percent Difference			
	1	2	3	4		1	2	3	4
3-5	0.23	0.13	0.21	0.09	0.29	7.7	20.5	10.3	25.6
11-12	0.19	0.11	0.13	0.08	0.18	1.3	9.0	6.4	12.8
29-31	0.03	0.01	0.01	0.06	0.03	0.0	2.3	2.3	3.8
44-63	0.01	0.01	0.01	0.01	0.01	0.0	0.0	0.0	0.0

Key

Column 1 refers to the Light Character
Column 2 refers to the Slanted Character
Column 3 refers to the Hand-Printed Character
Column 4 refers to the Script Character

Chapter 4

SUMMARY

Analysis of Results

When analyzing the results, the main objective of this paper should not be forgotten. Although the characterization of a reference alphabet was frequently mentioned and used, this was done only as a means to an end and not as a final result. This means that the establishment of characterized reference letters were used as a measure of the process, and the actual end result was whether or not the techniques used would give unique representations.

Because of the Fourier Transform properties, there should be no doubt that the representation obtained for a particular normalized matrix was unique. However, because of the limited resolution used in a matrix, it would be possible to have two different characters with equivalent matrices which would result in identical magnitude spectra. So the first weak point in the process as outlined by this thesis was the degree of resolution necessary to avoid duplicate matrices for different letters. Since the ideal case of infinite resolution was not practical, the decision of how much resolution to use was based on the limitations placed on the process. Of these limitations the two most important were the time required to character recognize a symbol and the maximum distortion of any letter.

These two requirements were not independent of each other; in fact one was directly related to the other. This was easily understood because as a symbol's distortion increases so does the resolution necessary to define the character. The results were more data points to be transformed which took longer computer time.

There was only one other point in the recognition scheme that could invalidate this system. This weak point was in the method used to characterize a reference letter. The characterization of reference symbol was based on the similarities between its magnitude spectrum and those of the same letter but with distortions introduced. For the purposes of this thesis, visual means for defining the similarities sufficed, but for a working system better recognition methods would be needed. Several possibilities were discussed previously; however, along with these methods the maximum allowable distortion must again be considered before setting error criteria.

Any further investigation into the procedure outlined in this thesis should be directed toward the recognition process. Although two weak points were discussed, the problem of matrix resolution was only a difficulty for the particular considerations of this paper. The resolutions which are obtainable by optical scanning are more than adequate for a working system. So the need for an automated recognition process is paramount, and one of the major considerations of such a process would be control of the error parameters. This control would be ncessary in order to obtain a valid and unique representation for each member of the reference set.

Although the technique, as described by this thesis, did allow for character recognition of distorted symbols, it did not completely solve the other problems encountered by an actual working system.

Appendix A

Reference Set

This appendix contains those reference characters not previously discussed. Their magnitude spectra, which resulted from the computer program of Appendix B, are also included.

B

Figure 25A Reference Character B

C

Figure 26A Reference Character C

D

Figure 27A Reference Character D

F

Figure 28A Reference Character F

G

Figure 29A Reference Character G

H

Figure 30A Reference Character H

I

Figure 31A Reference Character I

J

Figure 32A Reference Character J

K

Figure 33A Reference Character K

L

Figure 34A Reference Character L

M

Figure 35A Reference Character M

N

Figure 36A Reference Character N

O

Figure 37A Reference Character O

P

Figure 38A Reference Character P

Q

Figure 39A Reference Character Q

T

Figure 40A Reference Character T

U

Figure 41A Reference Character U

V

Figure 42A Reference Character V

W

Figure 43A Reference Character W

X

Figure 44A Reference Character X

Y

Figure 45A Reference Character Y

Z

Figure 46A Reference Character Z

Figure 25B Magnitude Spectrum for Reference Character B

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CHARACTERIZATION OF THE ALPHABET FOR DIGITAL PROCESSING.(U)
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UNCLASSIFIED AFIT-CI-78-20 NL

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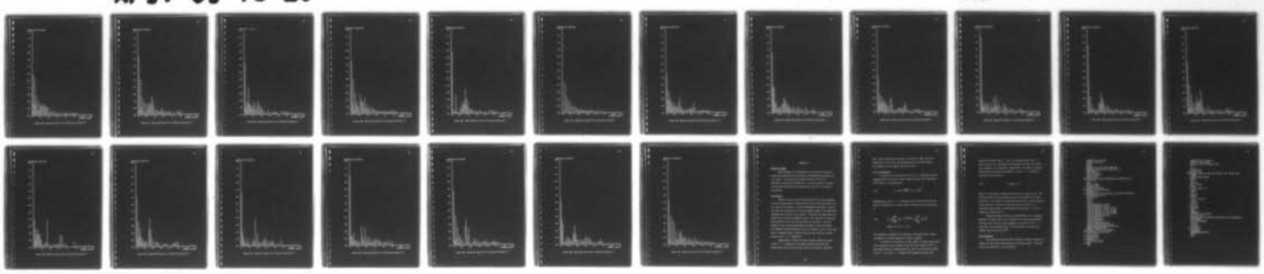

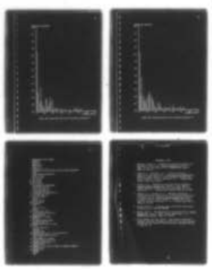

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DATE
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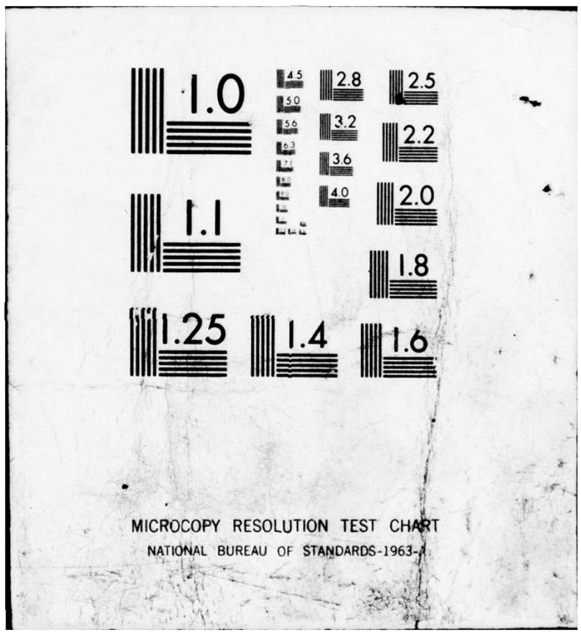
1.0
1.1
1.25
1.4
1.6
1.8
2.0
2.2
2.5
2.8
3.2
3.6
4.0
4.5
5.0
5.6
6.3
MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

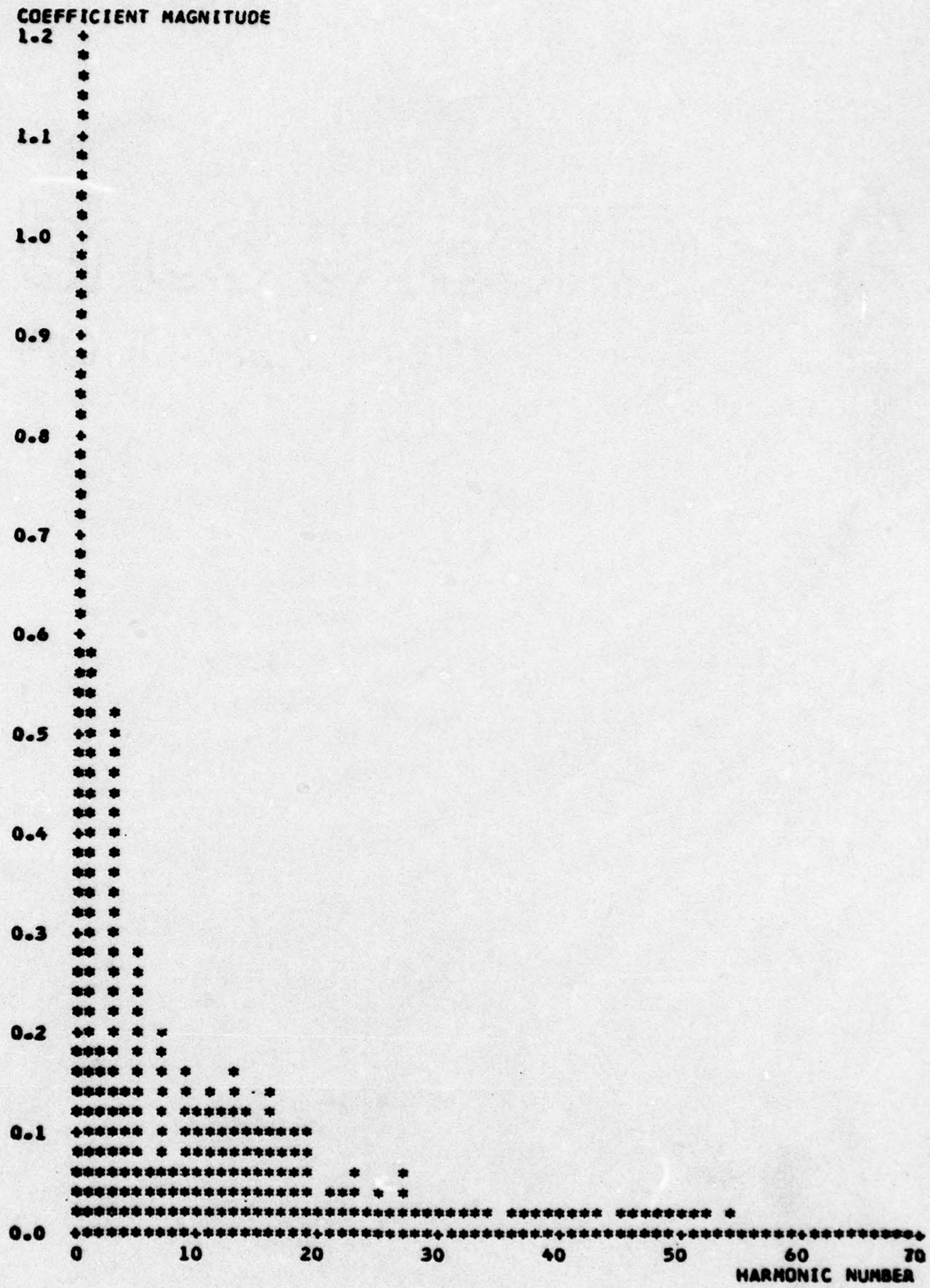

Figure 26B Magnitude Spectrum for Reference Character C

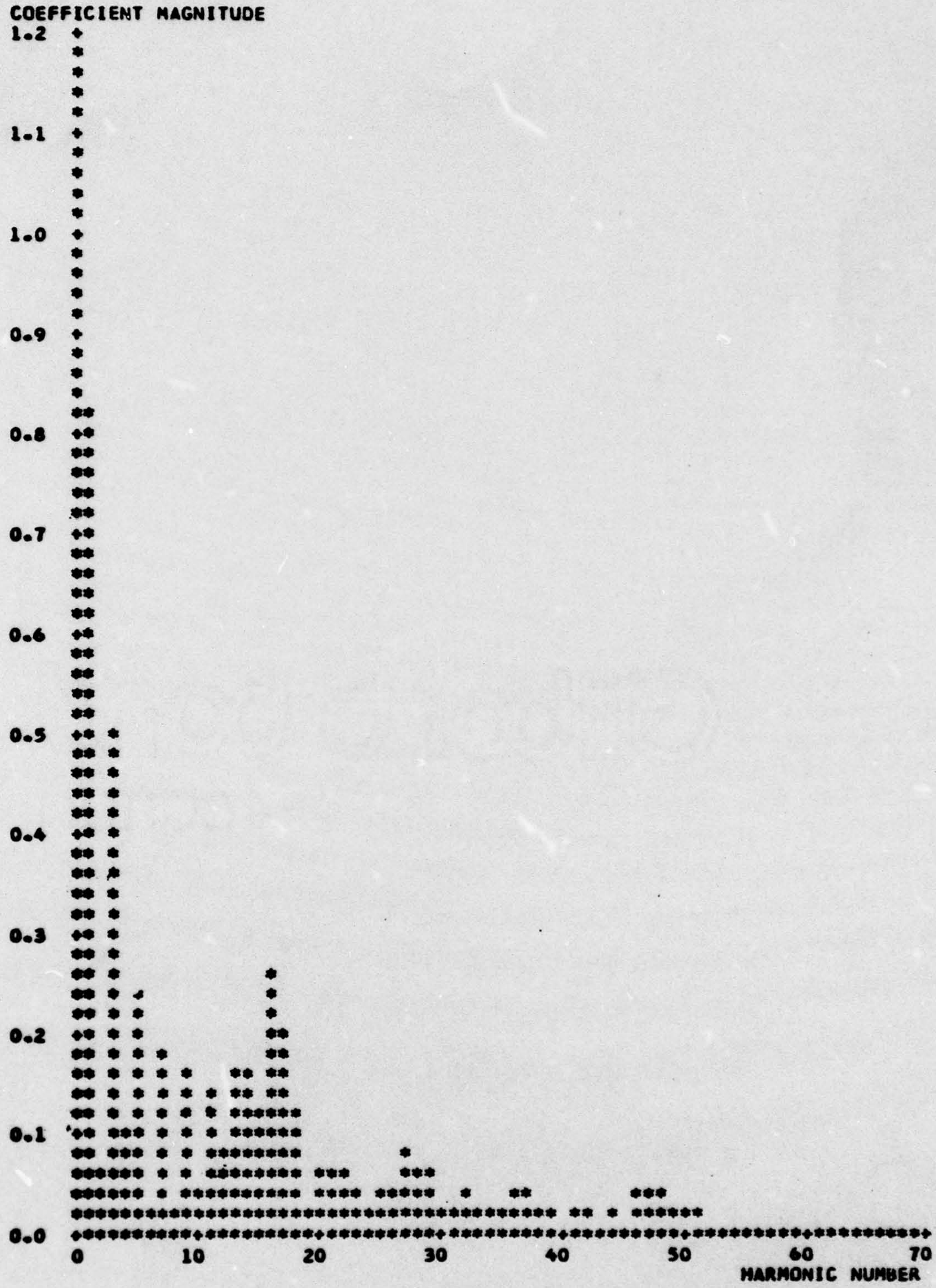

Figure 27B Magnitude Spectrum for Reference Character D

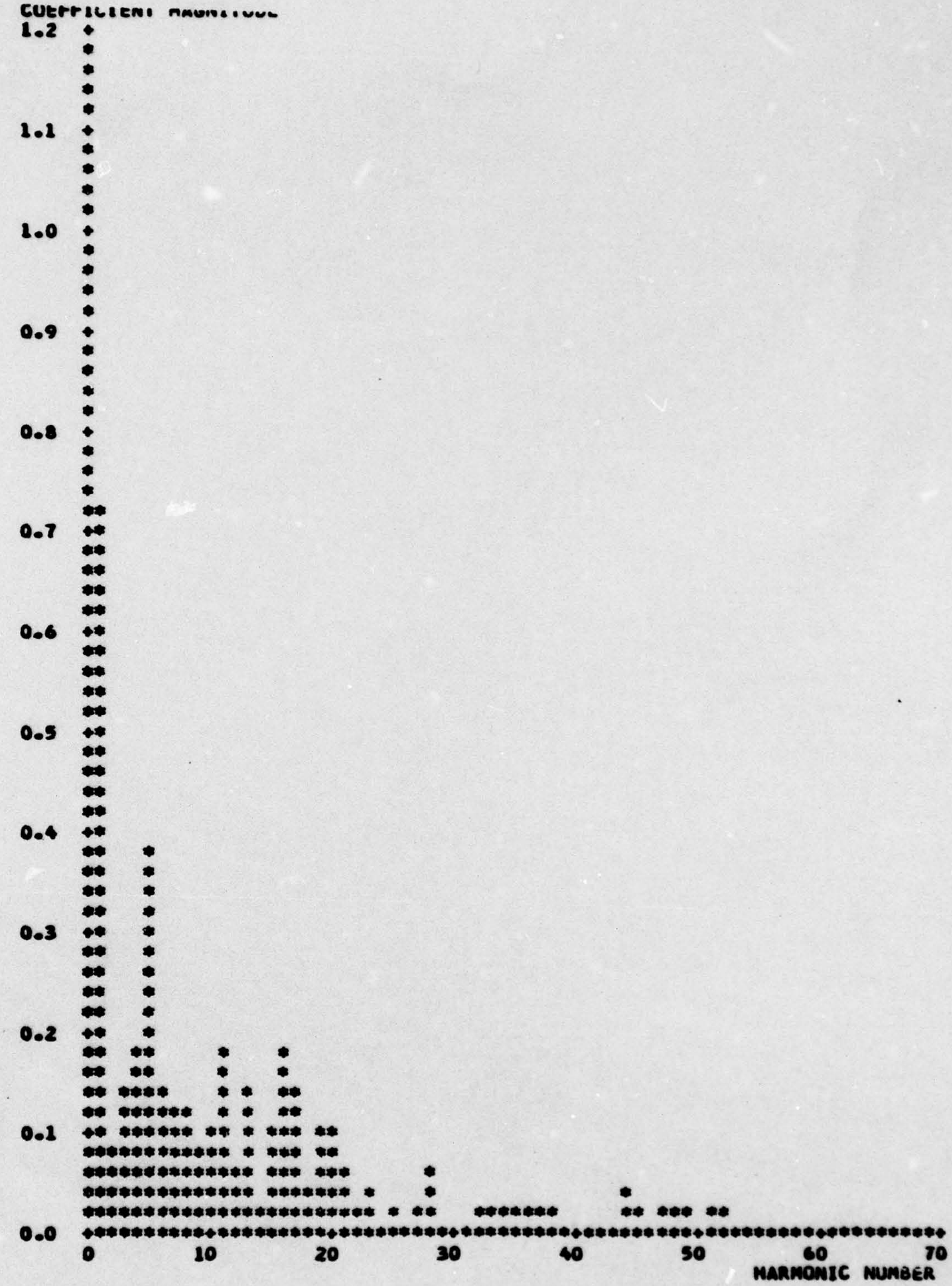

Figure 28B Magnitude Spectrum for Reference Character F

Figure 29B Magnitude Spectrum for Reference Character G

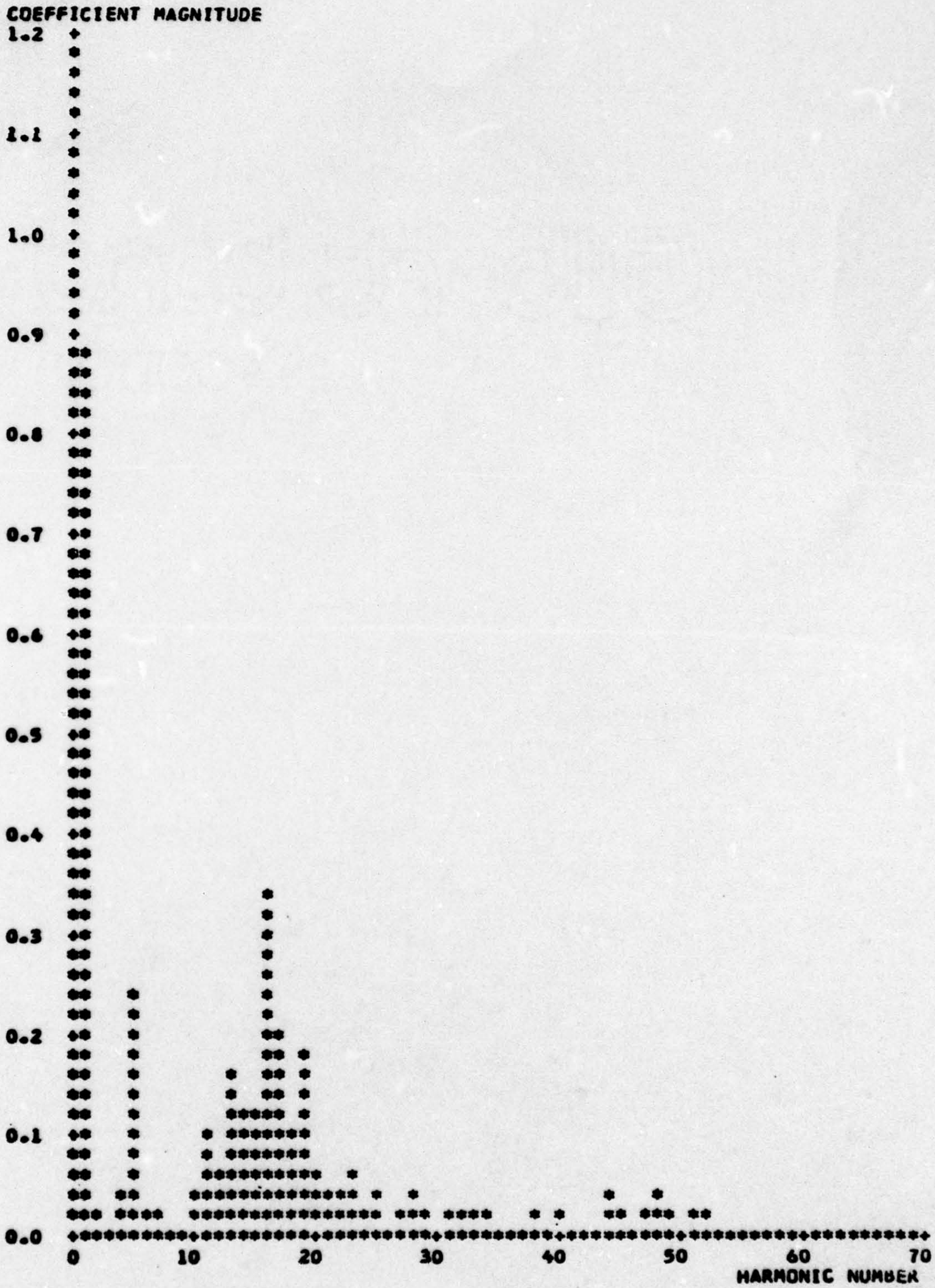

Figure 30B Magnitude Spectrum for Reference Character H

Figure 31B Magnitude Spectrum for Reference Character I

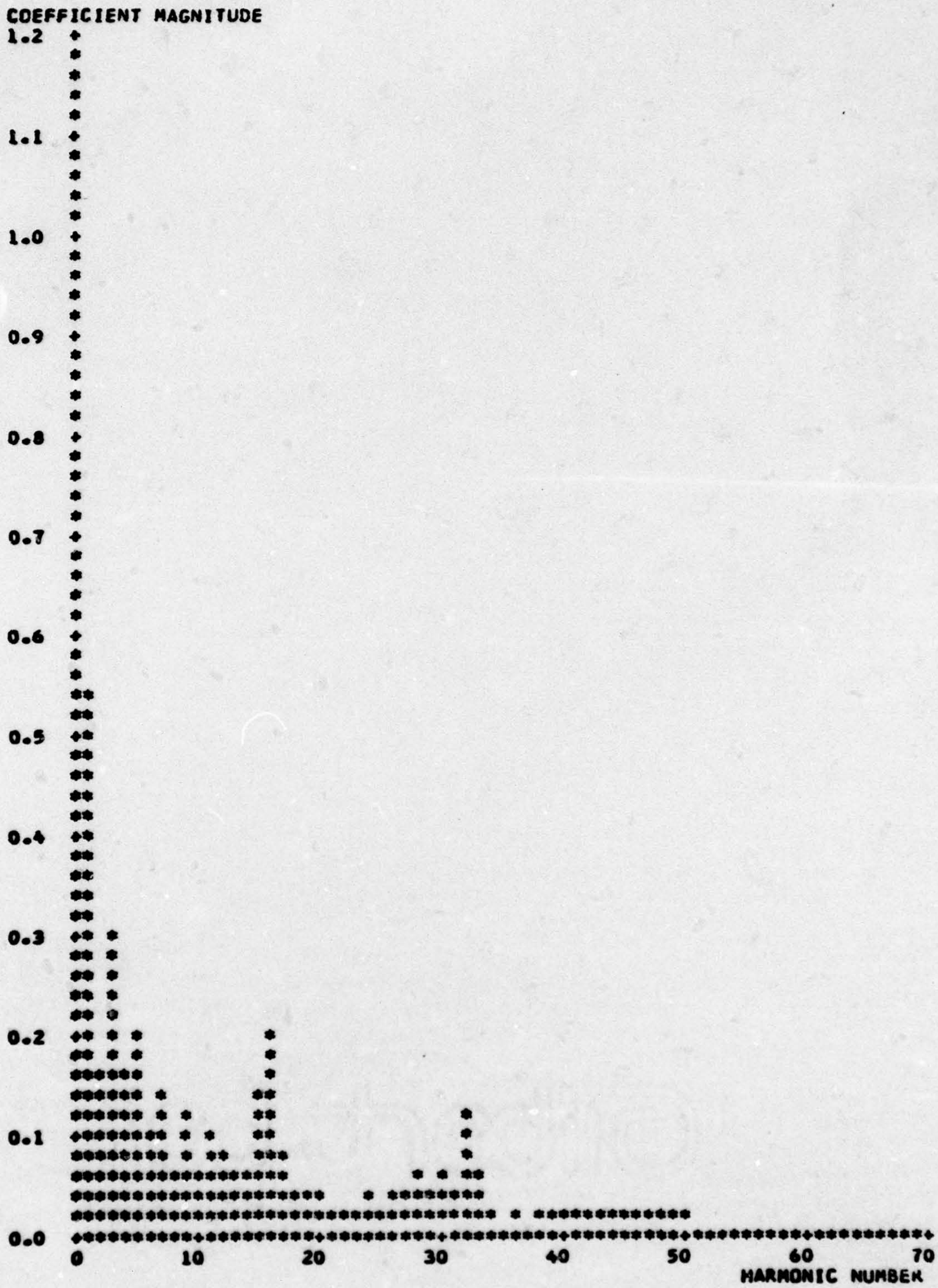

Figure 32B Magnitude Spectrum for Reference Character J

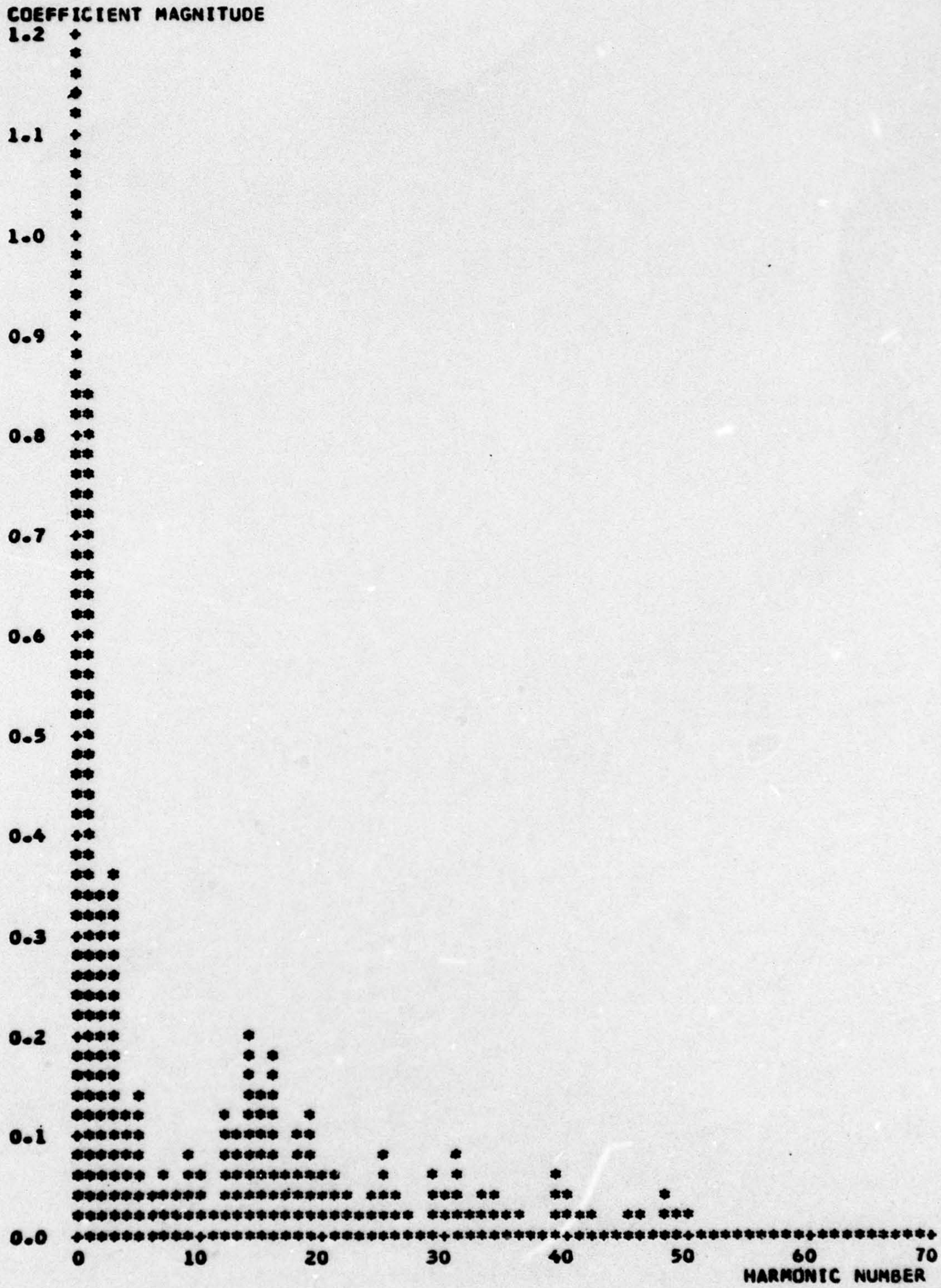

Figure 33B Magnitude Spectrum for Reference Character K

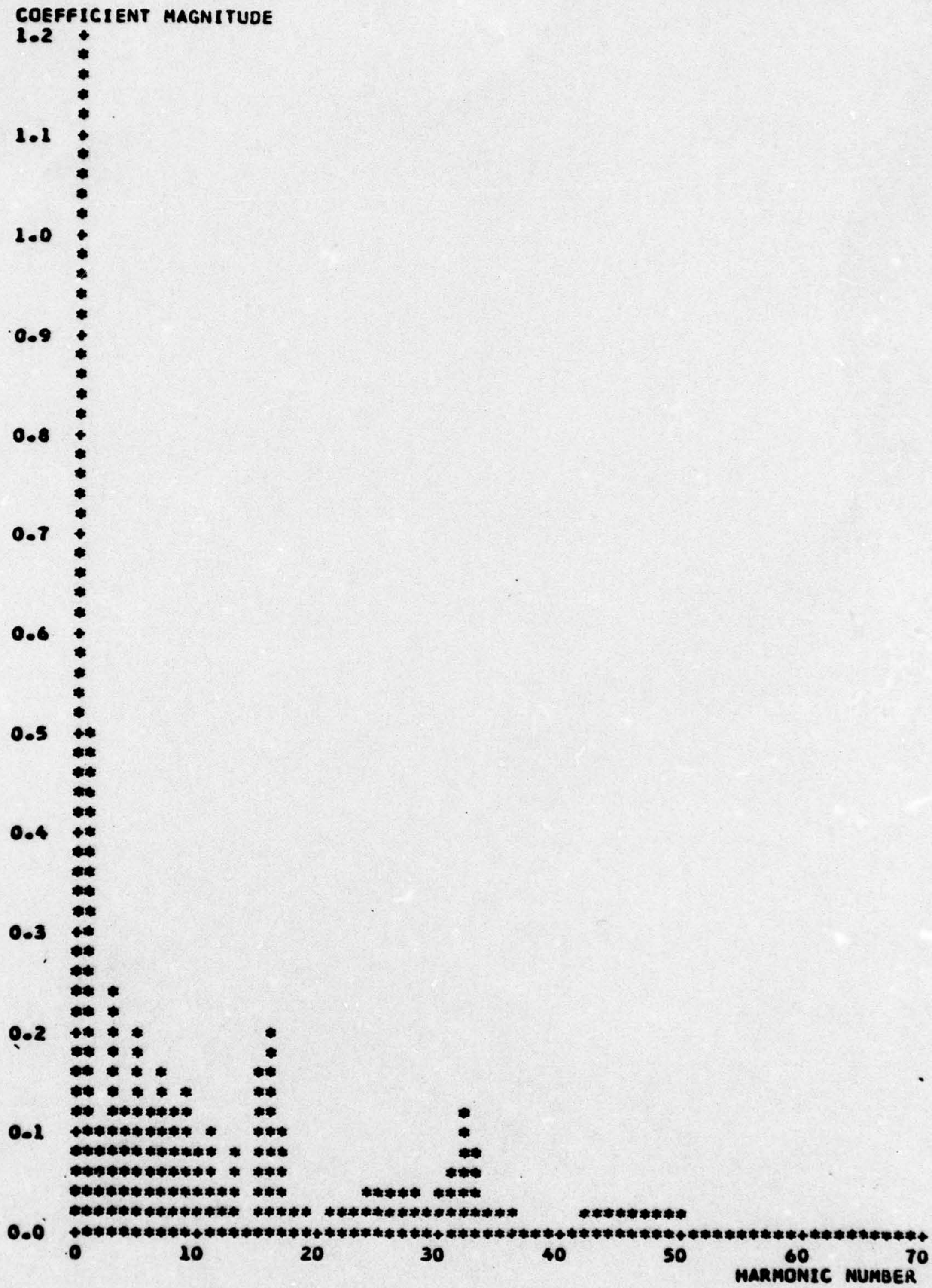

Figure 34B Magnitude Spectrum for Reference Character L

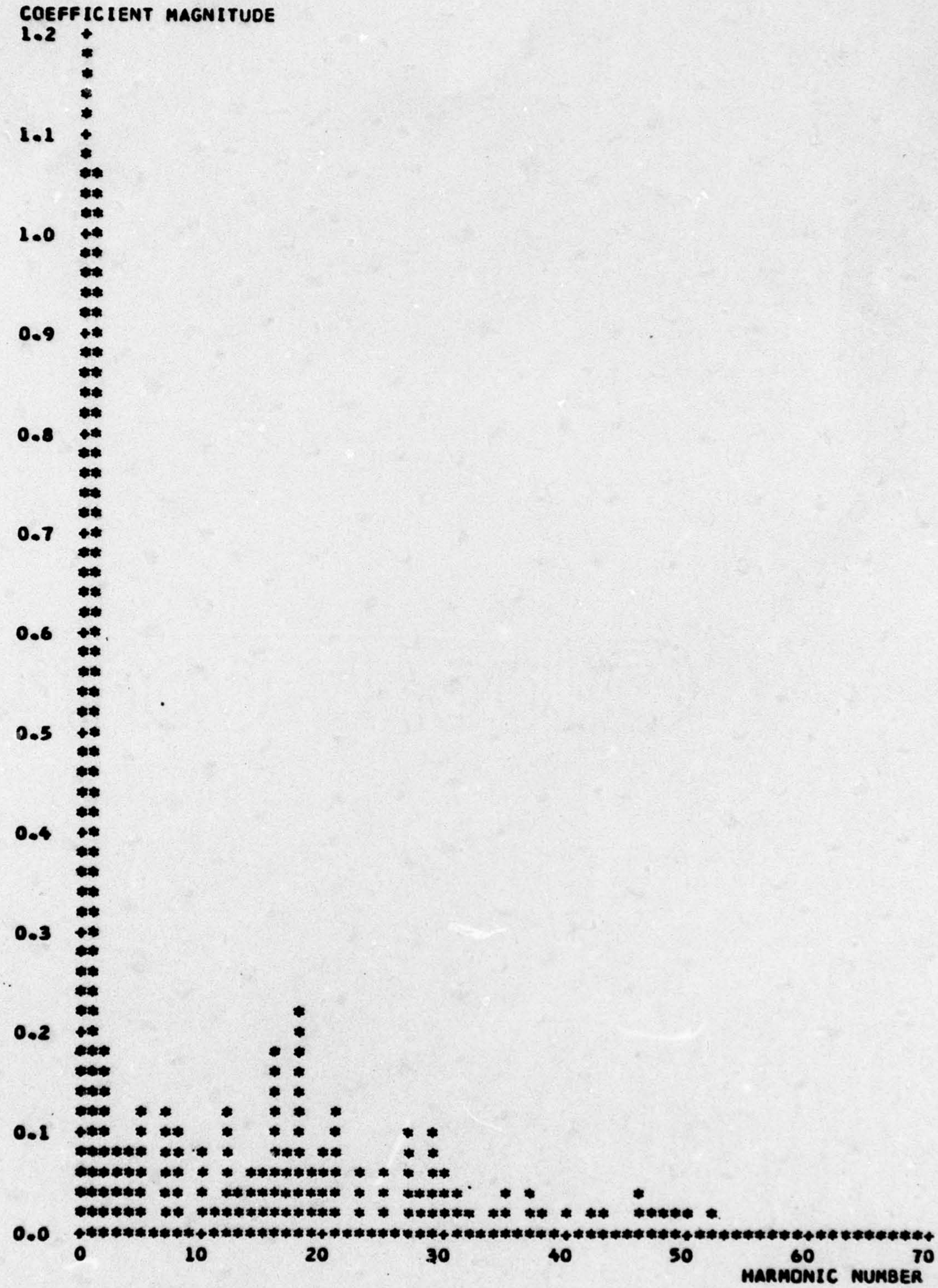

Figure 35B Magnitude Spectrum for Reference Character M

Figure 36B Magnitude Spectrum for Reference Character N

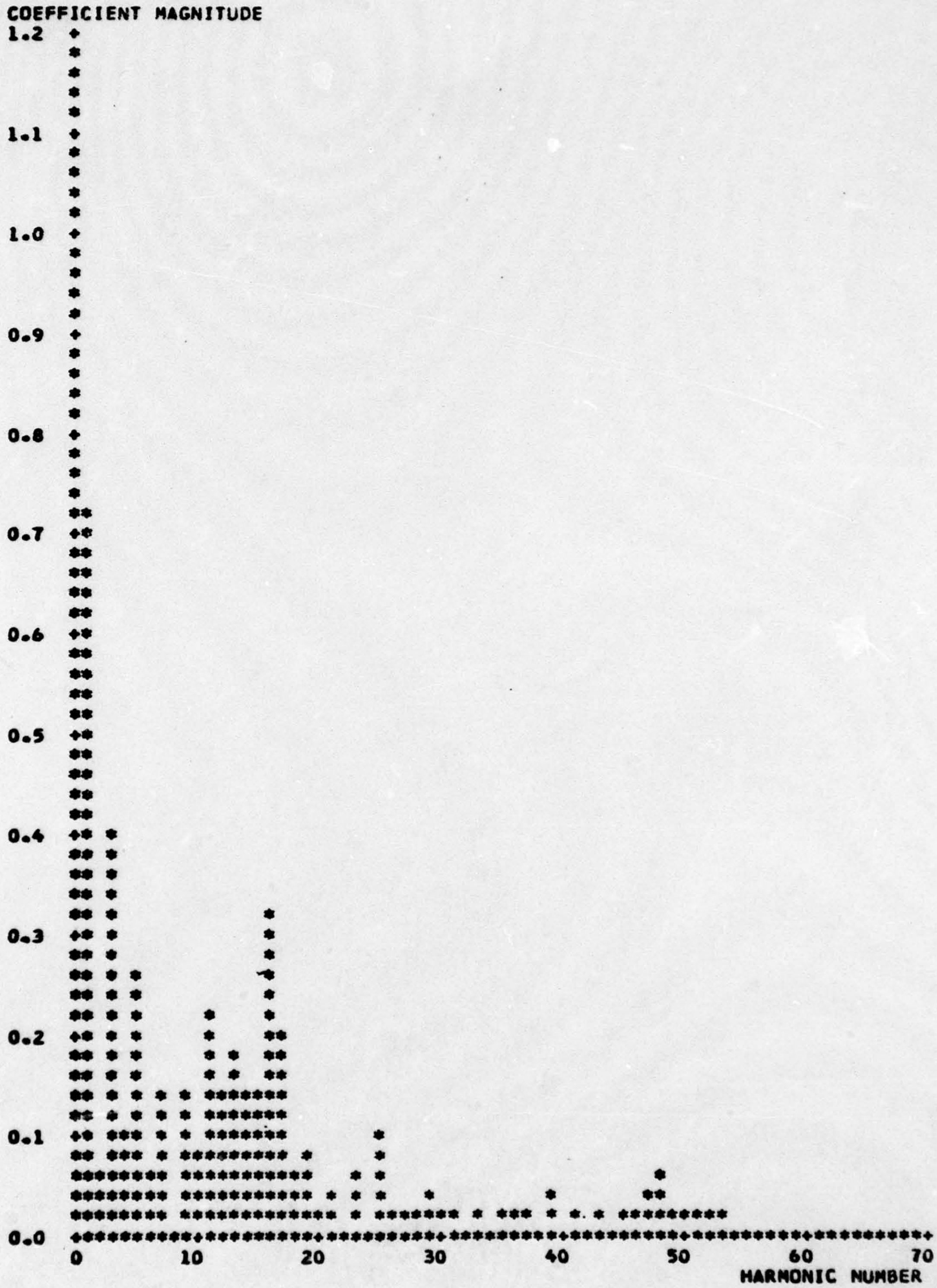

Figure 37B Magnitude Spectrum for Reference Character 0

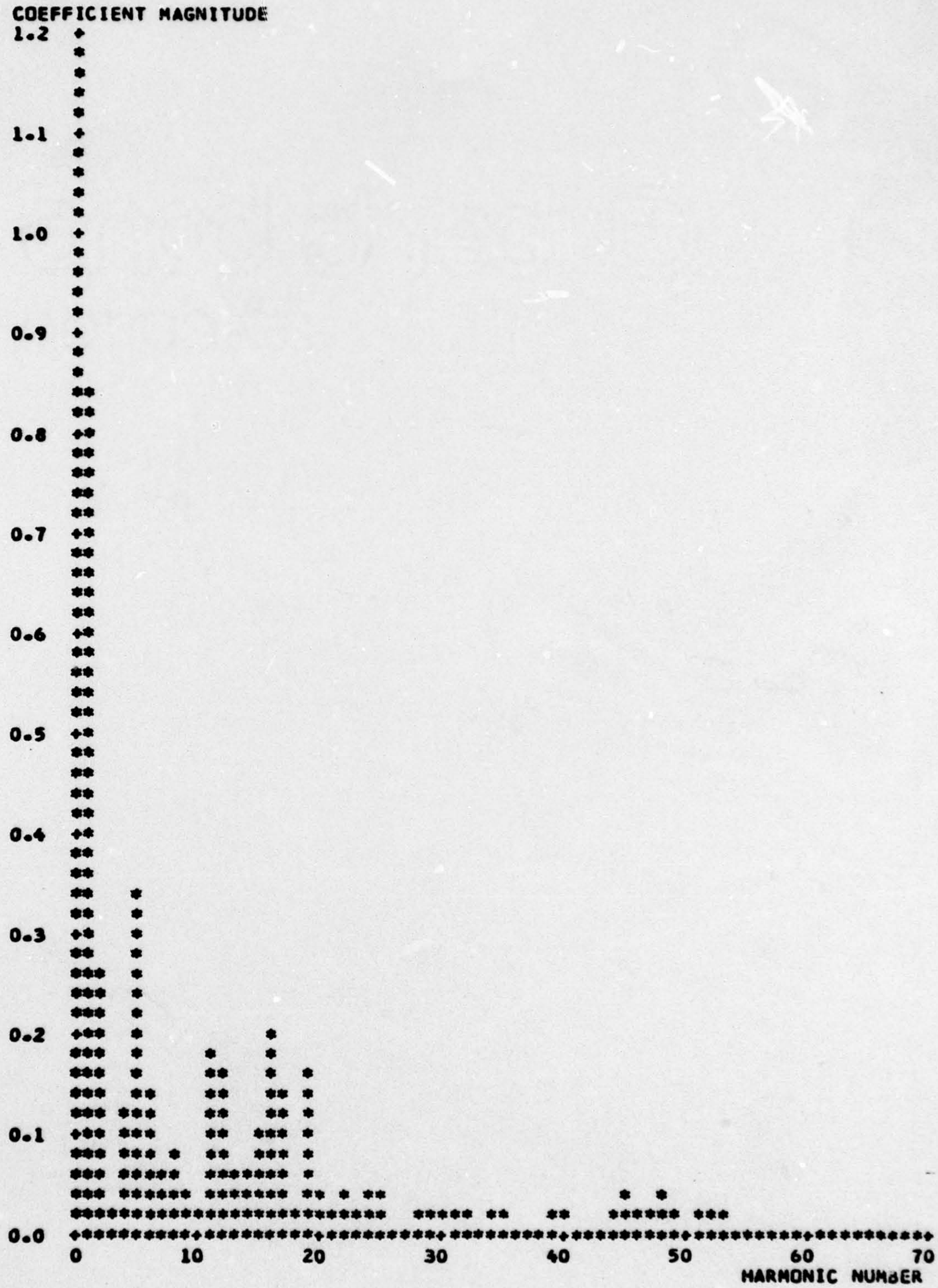

Figure 38B Magnitude Spectrum for Reference Character P

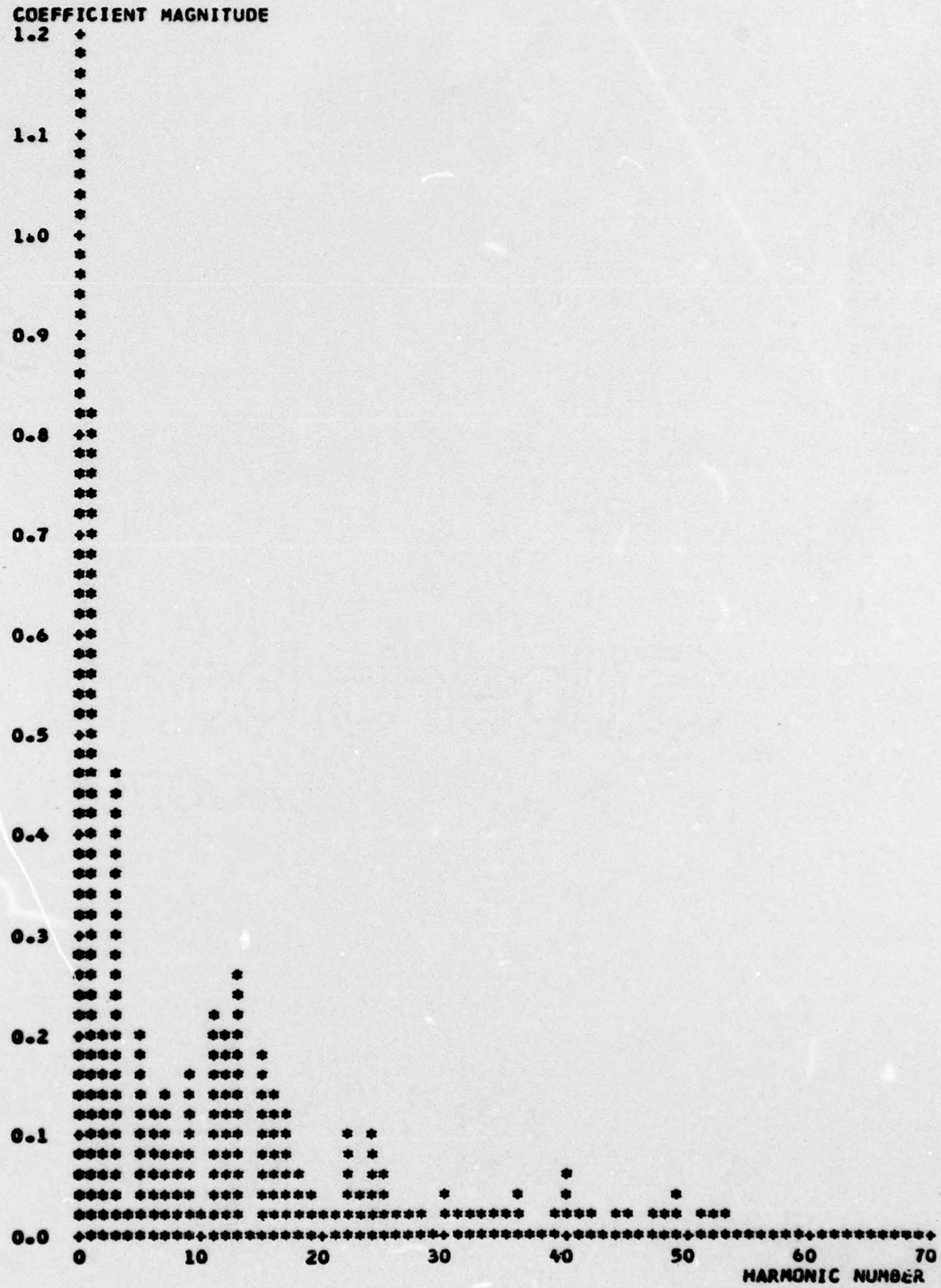

Figure 39B Magnitude Spectrum for Reference Character Q

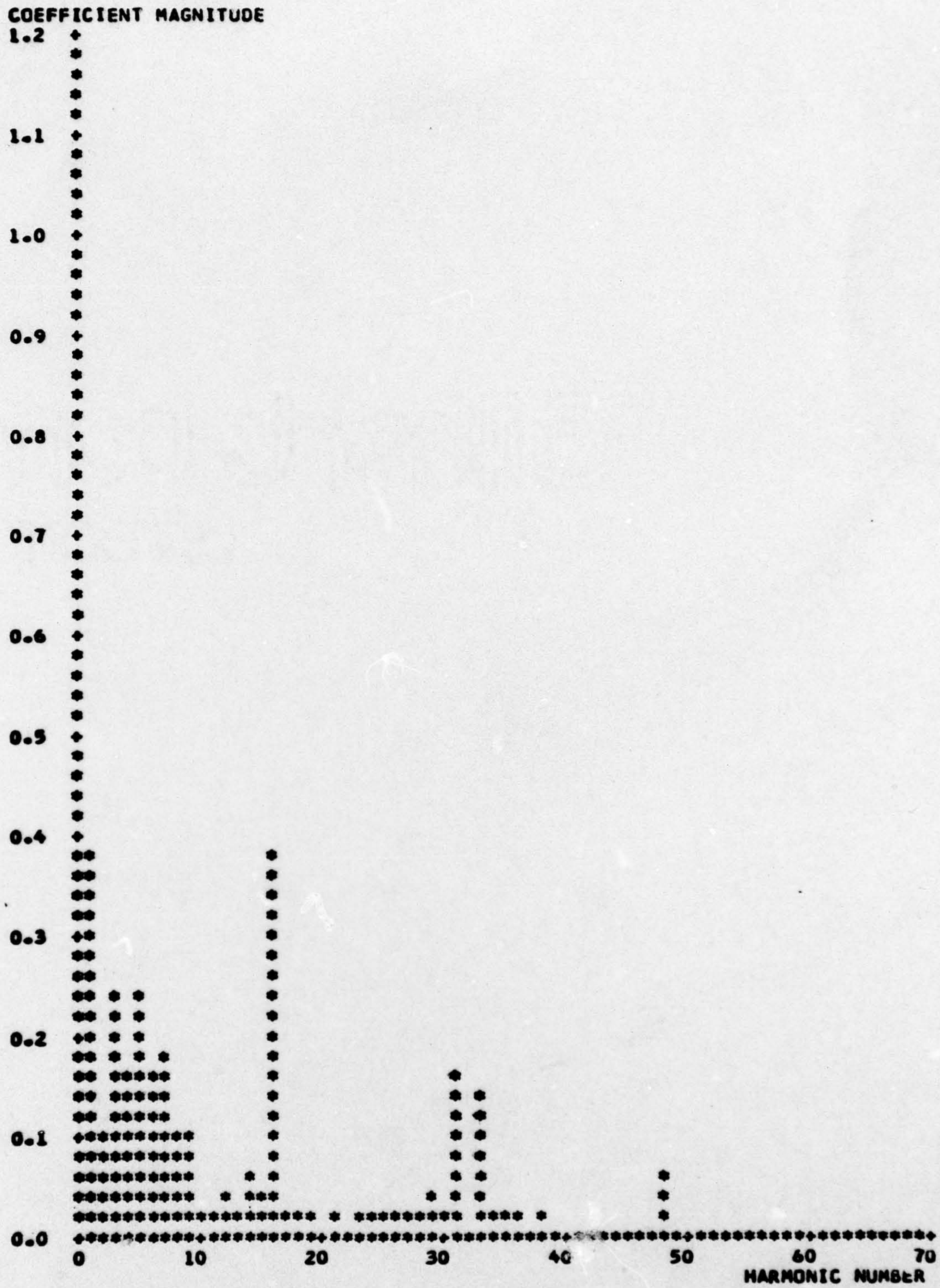

Figure 40B Magnitude Spectrum for Reference Character T

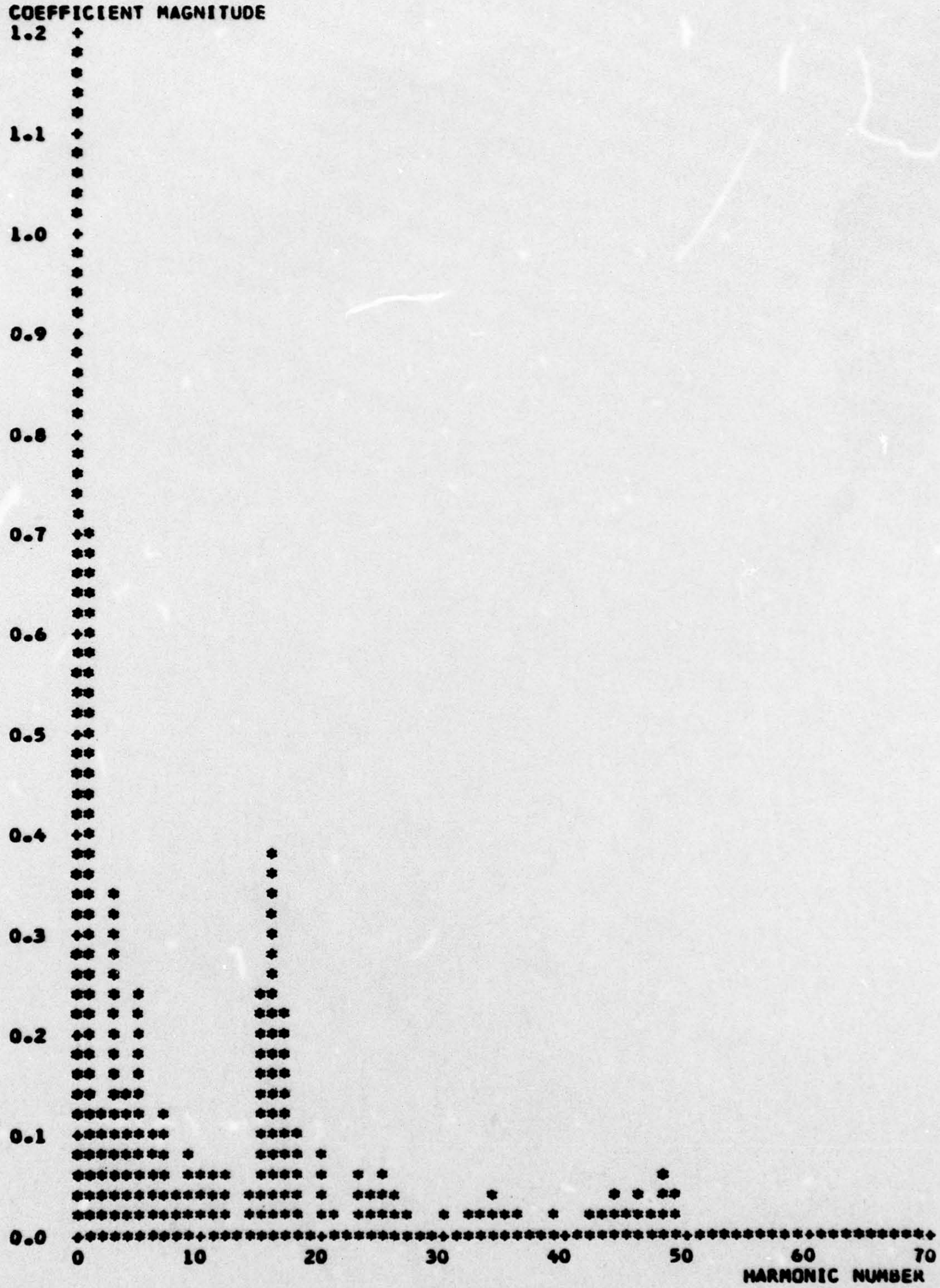

Figure 41B Magnitude Spectrum for Reference Character U

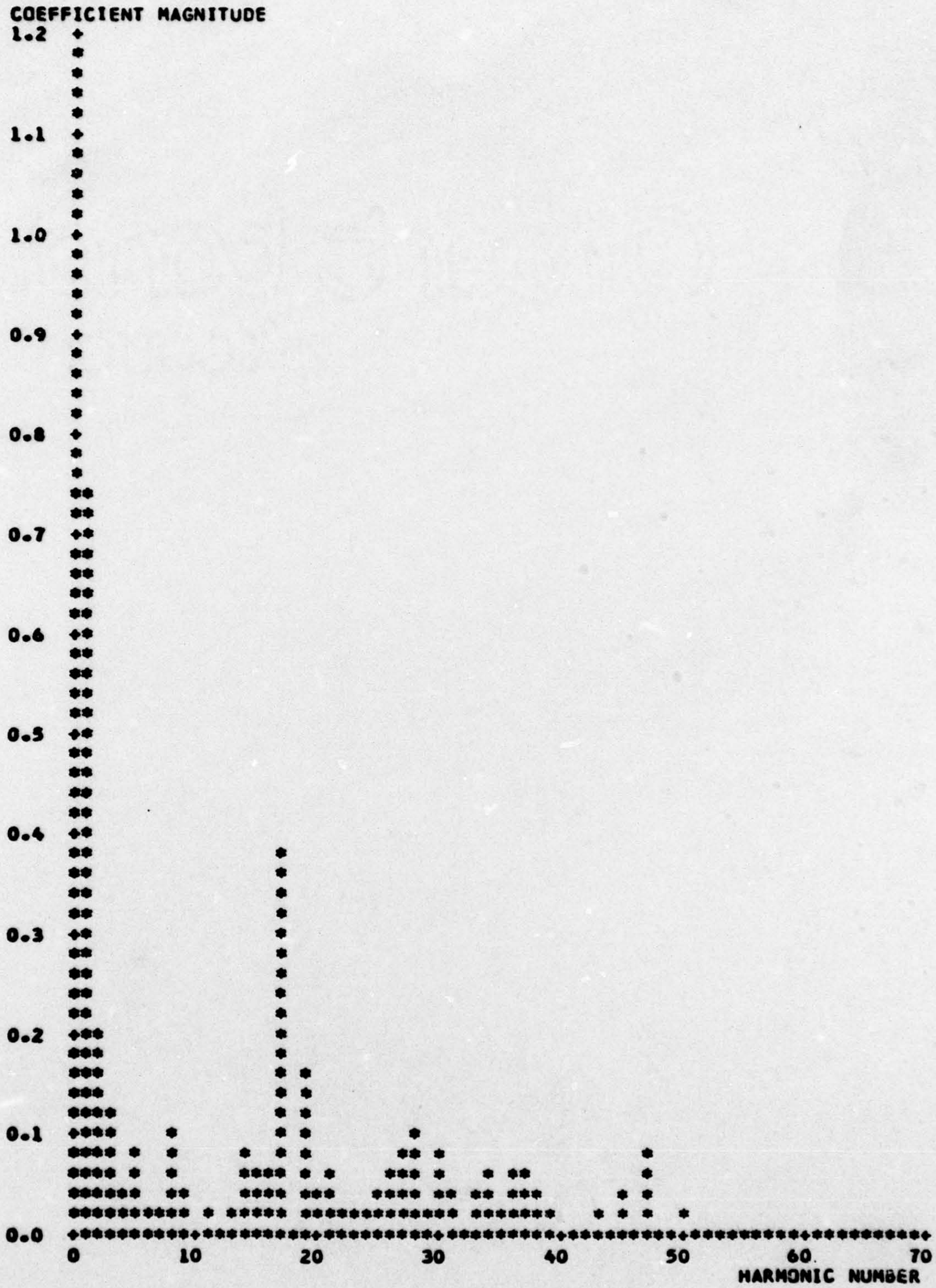

Figure 42B Magnitude Spectrum for Reference Character V

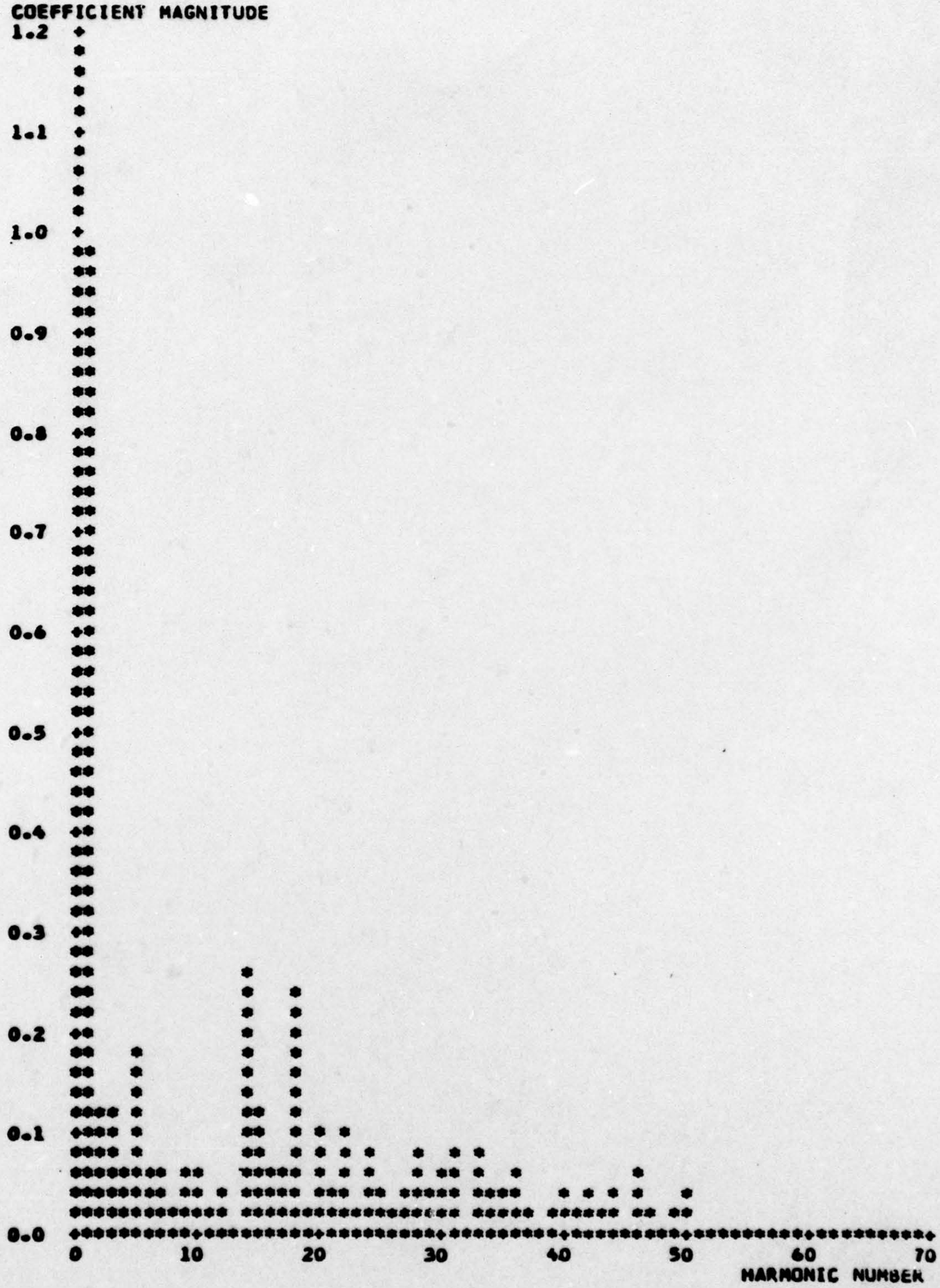

Figure 43B Magnitude Spectrum for Reference Character W

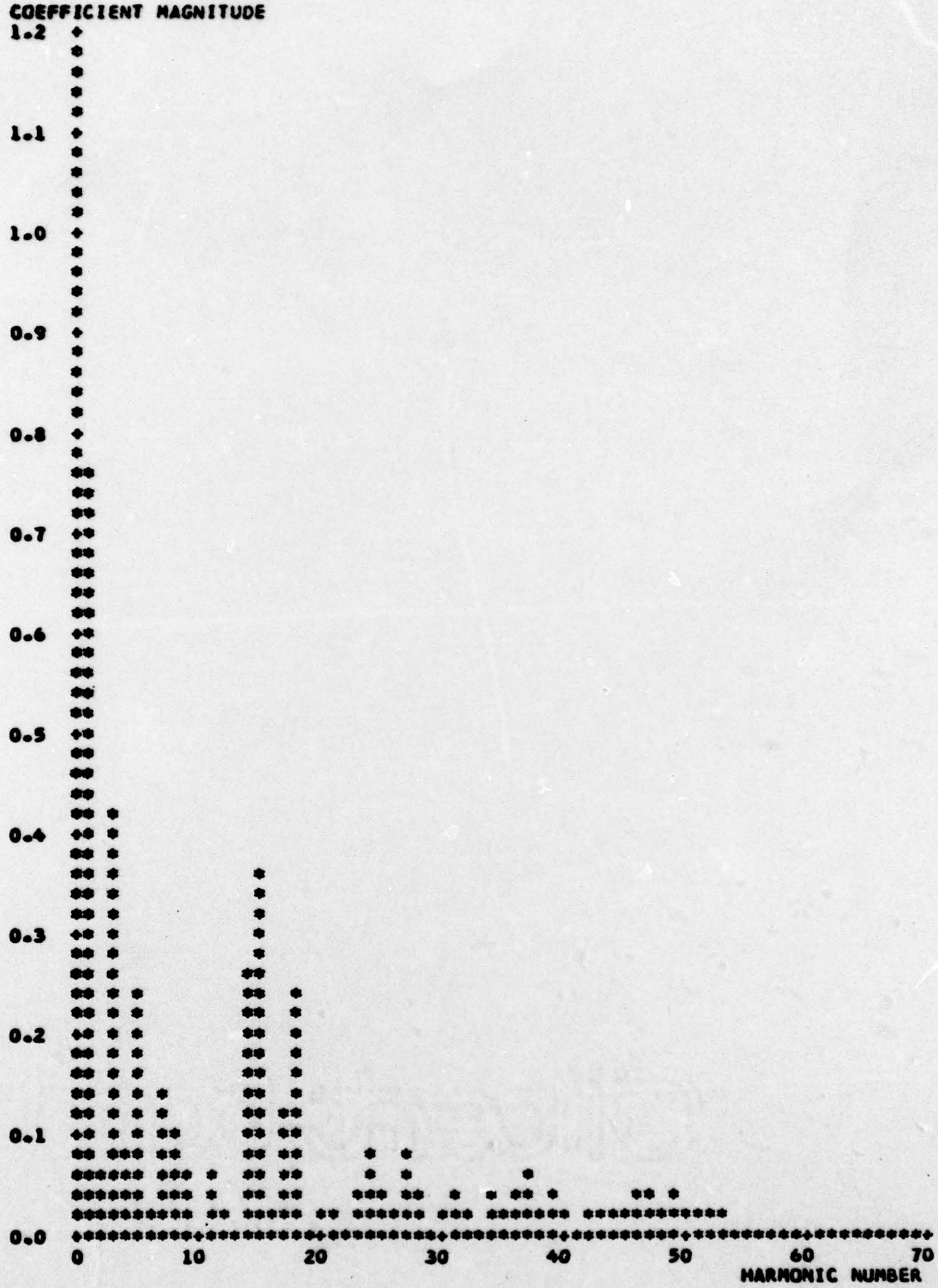

Figure 44B Magnitude Spectrum for Reference Character X

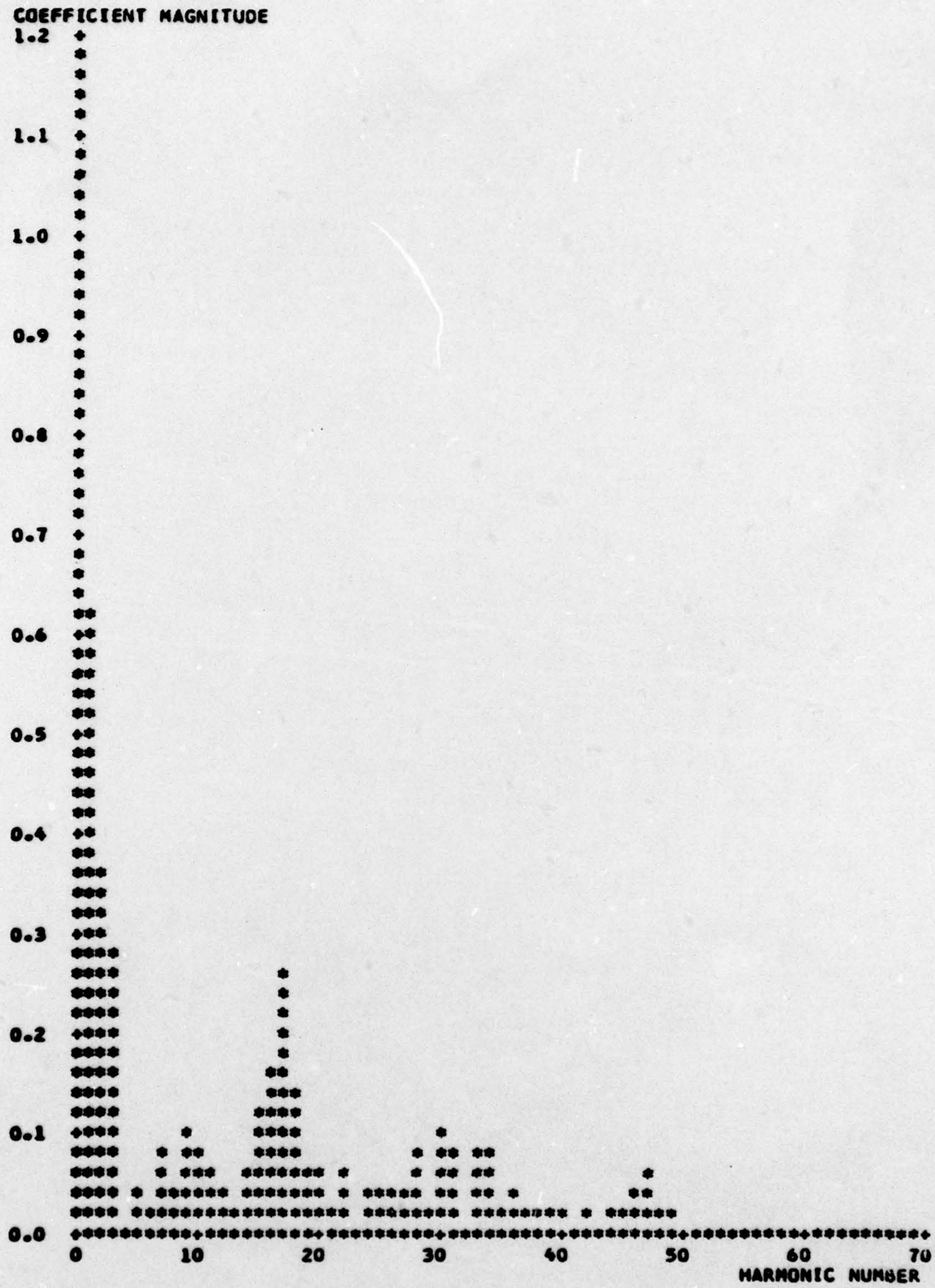

Figure 45B Magnitude Spectrum for Reference Character Y

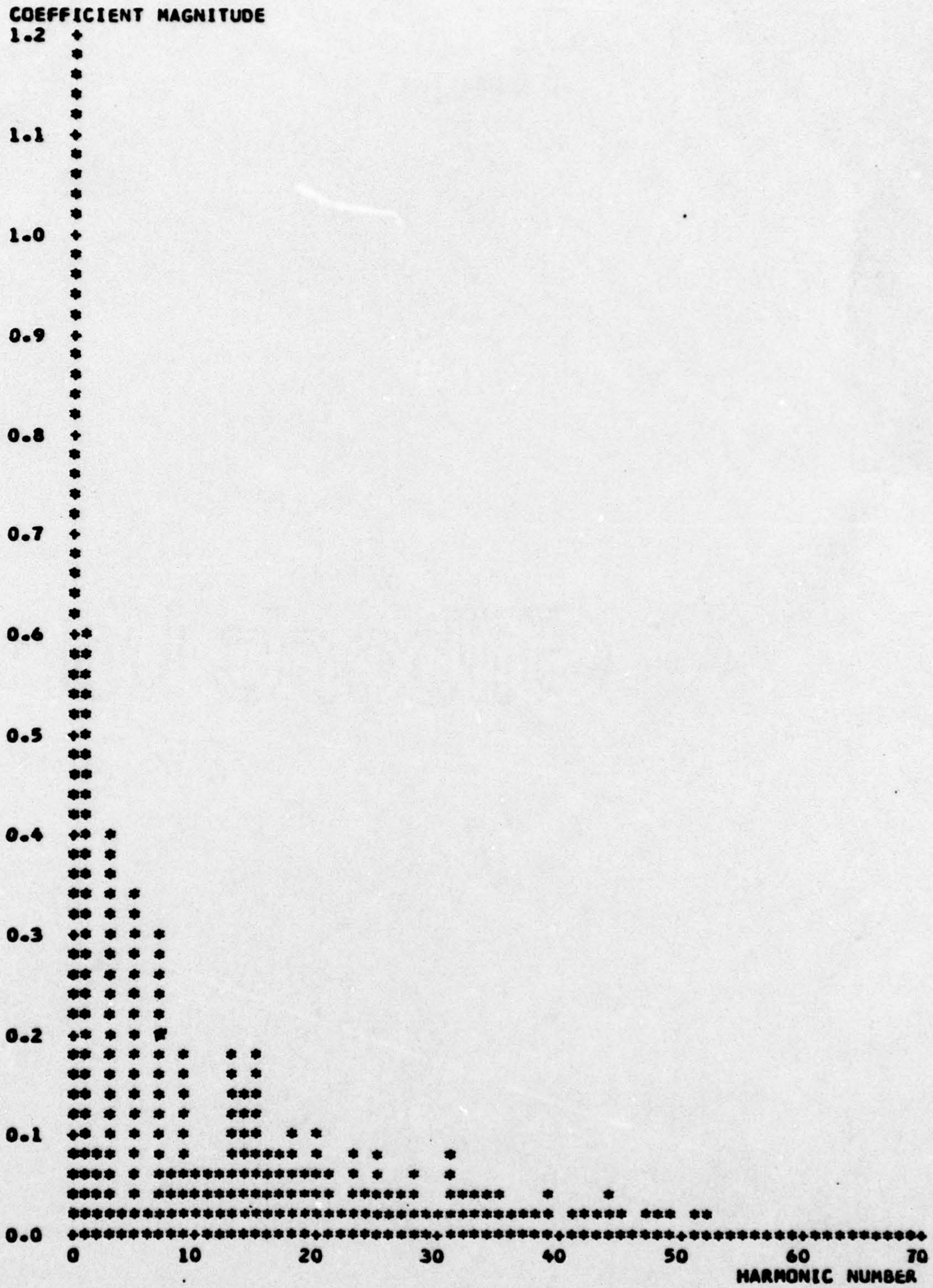

Figure 46B Magnitude Spectrum for Reference Character Z

Appendix B

Computer Program

The following is an explanation in the use of the computer program that was used for the purpose of obtaining data necessary for this thesis. A listing of the program written in Fortran IV immediately follows this explanation. Since the program is divided into the main program and two subroutines, each part is discussed individually.

Main Program

The main program basically consisted of the calling sequences for the two subroutines, a manipultation of data into the correct form for use by the subroutines, and the input/output operations. Because the input has the possibility of being complex numbers, the read format statement must take this into account. Therefore, the input should be broken into its real and imaginary parts. The real parts of the data were placed first on the cards according to the format. Then the imaginary parts of the data followed according to the same format. This method of reading placed the real and imaginary parts of each data point in adjacent memory locations which was the necessary arrangement for the F. F. T. subroutine.

Manipulation of data by the main program changed the output of the F. F. T. subroutine into complex numbers which were the coefficients of the sine and cosine terms in the Fourier expansion.

Then, these coefficients were used to calculate a number which was proportional to the total root-mean-square value at each harmonic. This number was to be used by the plot routine.

F. F. T. Subroutine

The basis for the algorithm of the F. F. T. subroutine was the composite nature of certain integer numbers and the cyclic properties of W^{jk} where W is represented as

$$W = \exp\left(\frac{-i2\pi}{N}\right) \text{ and } i = \sqrt{-1} \qquad (8)$$

Mathematically, the F. F. T. subroutine was derived from the Discrete Fourier Transform (D.F.T.) whose forward transform can be represented as

$$a_j = \frac{1}{N}\sum_{k=0}^{N-1} x(k)\ e^{(-i2\pi jk/N)} = \frac{1}{N}\sum_{k=0}^{N-1} x(k)\ W^{jk} \qquad (9)$$

where $j = 0,1,2,\ldots..N-1$

This equation is already in an algorithmic form which can be readily programmed as a single program on a digital computer.

By placing a limitation on N (the number of complex data points) which required it to be a power of two, the cyclic nature of W^{jk}, as mentioned previously, became apparent in that its only possible values were +1, -1, +i, and -i. In general W^{jk} repeated with every four

consecutive integer numbers. Thus, by prearranging the data in a specific order, this repetition could decrease the number of calculations necessary for a transform. Specifically, the number of complex multiplications and additions necessary in the F. F. T. subroutine contained in this thesis is

$$N \log_2 N \quad (7) \tag{10}$$

where N is the number of complex data points and a power of two. The savings provided by this subroutine were very substantial for large values of N. For example, the DFT would require over a million complex multiplications to transform 1,024 data points, but the F. F. T. subroutine required about 5,000 complex multiplications. This was a reduction of about 200 to 1.

Besides performing the actual transformation, this subroutine checked N to assure that it was a power of two, and also preshuffled the input data into the correct sequence as required by the F. F. T. algorithm. The preshuffling was strictly based on N and the four-integer-repetition cycle of W^{jk}.

Plot Subroutine

The plotting subroutine takes information already contained in memory and plots these values against the harmonic number. The scale factors are also set in this subroutine.

```
      INTEGER X1,Y1,W1,W2,W3
      COMPLEX RK,SK,TK,VI
      N=128
      W1=N/2
      DIMENSION A(2,128),X(64),ARMS2(64)
      READ(5,1)((A(X1,Y1),Y1=1,128),X1=1,2)
    1 FORMAT(8F5.1)
      CALL FFT(A,N,-1)
      CON=1./FLOAT(N)
      WRITE(6.100)
  100 FORMAT(1H1,19X,1HJ,4X,8HRE(A(J)),4X,8HIM(A(J))//)
      DO 2 I=1,N
      K=I-1
      AR=A(1,I)*CON
      AI=A(2,I)*CON
    2 WRITE(6,110)K,AR,AI
  110 FORMAT(18X,I3,2(4X,F8.5))
      WRITE(6,112)
  112 FORMAT(1H1,11X,1HK,13X,4HR(K),25X,4HS(K),25X,4HT(K),
     *15X,8HRMS(K)*2,5X,//)
      DO 95 I=1,W1
      VI=(0,1)
      K=I-1
      L=N-K+1
      IF(K.EQ.0)AA=(A(1,I))*CON
      IF(K.EQ.0)BB=(A(2,I)*CON
      IF(K.GT.0)AA=(A(1,I)+A(1,L))*CON
      IF(K.GT.0)BB=(A(2,I)+A(2,L))*CON
      IF(K.GT.0)DD=(A(1,I)-A(1,L))*CON
      IF(K.GT.0)EE=(A(2,I)-A(2,L))*CON
      IF(K.EQ.0)RK=CMPLX(AA.BB)
      IF(K.EQ.0)SK=(0,0)
      IF(K.EQ.0)TK=(0.0)
      IF(K.GT.0)RK=(0.0)
      IF(K.GT.0)SK=CMPLX(AA.BB)
      IF(K.GT.0)TK=(CMPLX(DD,EE))*VI
      ARMS21=CABS(CSQRT((SK**2)+(TK**2)))
      ARMS2(I)=ARMS21*1000.0
   95 WRITE(6,111)K,RK,SK,TK,ARMS21
  111 FORMAT(10X,I3,7(4X,F10.6))
      DO 94 I=1,W1
   94 X(I)=FLOAT(I)
      WRITE(6,113)
  113 FORMAT('1')
      CALL PLOT(X,ARMS2)
   86 STOP
      END
```

```
      SUBROUTINE FFT(D,N,NSIGN)
      COMPLEX T,D(N),W,WARG
      TEST THAT INPUT IS POWER OF TWO
      I=1
    1 I=I+I
      IF(I-N)1,3,2
    2 WRITE(6,100)
  100 FORMAT(1X,40HDATA BLOCK NOT POWER OF TWO. CAN NOT RUN)
      RETURN
      START OF DATA SHUFFLE
    3 NHF=N/2
      J0=0
      LAST=N-2
      DO 8 I=2,LAST
      M=NHF
    4 IF(J0.LT.M)GO TO 5
      J0=J0-M
      M=M/2
      GO TO 4
    5 J0=J0+M
      J=J0+1
      IF(I.GE.J)GO TO 8
      T=D(J)
      D(J)=D(I)
      D(I)=T
    8 CONTINUE
      BEGIN FFT
      INC=1
      MNODES=2
    9 IF(MNODES.GT.N) RETURN
      DO 10 M=1,INC,1
      WARG=CMPLX(0.,6.2831853*FLOAT(NSIGN*(M-1))/FLOAT(MNODES))
      W=CEXP(WARG)
      DO 10 I=M,N,MNODES
      J=I+INC
      T=D(J)*W
      D(J)=D(I)-T
   10 D(I)=D(I)+T
      INC=MNODES
      MNODES=MNODES+MNODES
      GO TO 9
      END
```

```
      SUBROUTINE PLOT(X,ARMS2)
      XMAX=70.0
      XMIN=0.0
      YMAX=1200.0
      YMIN=0.0
      DATA IB,IA/' ','*'/
      DIMENSION IP1(70),IX1(8),IP(120,70),X(64),ARMS2(64)
      I=120
      YMAX1=(YMAX-YMIN/FLOAT(I)
      DO 92 L=1,120
      DO 2 K=1,70
    2 IP(L,K)=IB
   92 IP(L,K)=IB
    5 DO 3 J=1,64
      IY1=(ARMS2(J)-YMIN)/YMAX1
      IF(IY1.NF.I)GO TO 7
      IF(IY1.EQ.I)IY=IY1
      IF(IY1.EQ.I)GO TO 8
    7 IY=(ARMS2(J)-YMIN)/YMAX1+1.0
      IF(IY.NE.I)GO TO 3
    8 IX=(X(J)-XMIN-1
      IX3=IX
      DO 93 I3=1,IY
   93 IP(I3,IX3)=IA
    3 CONTINUE
      I1=I
      DO 91 I2=1,70
      IX2=I2
   91 IP1(I2)=IP(I1,IX2)
      IF((I/10)*10.EQ.I)GO TO 4
      WRITE(6,20)IP1
   20 FORMAT(11X,'*',70A1)
      GO TO 6
    4 YP=(YMAX1/1000)*I+YMIN
      WRITE(6,21)YP,IP1
   21 FORMAT(1X,F8.1,2X,'+',70A1
    6 I=I-2
      IF(I.GT.0)GO TO 5
      YP=YMIN
      WRITE(6,22)YP
   22 FORMAT(1X,F8.1,2X,'+',7('*********+'))
      XUNIT=((XMAX-XMIN)/70.)*10.
      DO 9 I=1,8
    9 IX1(I)=XUNIT*(I-1)+XMIN
      WRITE(6,12)(IX1(I),I=1,8)
   12 FORMAT(2X,8(7X,I3))
      WRITE(6,120)
  120 FORMAT('0',10X,'PLOT OF RMS*2 VS HARMONIC NUMBER')
      WRITE(6,114)
  114 FORMAT('1')
      RETURN
      END
```

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